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CCUS deployment challenges and opportunities for the GCC

A report prepared for the Oil and Gas Climate Initiative by AFRY & GaffneyCline

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OIL AND GAS CLIMATE INITIATIVE

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Executive Summary

Opportunities for CCUS in the GCC

CCUS has promising applications across multiple industrial activities in the GCC and will play a role in the decarbonisation of hard-to-abate industries. A high abundance of industries with high CO_2 emissions, high purity and high potential for capture position the GCC well in rapid decarbonisation of domestic industry particularly in the natural gas processing, fertilisers and petrochemical sectors.

The GCC can be a world class hub for CCUS, with significant potential in both depleted reservoirs and saline aquifers close to emissions clusters. This study has revealed significant subsurface potential for storage in the GCC, both in depleted gas reservoirs and saline aquifers, with the greatest opportunity found in the Rub'al Khali basin and in the sequences beneath Kuwait. Further work will be required to translate these findings into specific opportunities that can be matured into storage sites and linked with emissions clusters and potential hubs. Based on this study the current best guess storage capacity for the GCC is c. 170Gt of CO_2, equivalent to c. 230 years of current annual emissions of the GCC.

The GCC region has the potential to develop active CCUS hubs due to the availability of natural sinks and concentrated CO_2 emissions. Clusters of high purity, low cost capture industries (petrochemicals, fertilisers, methanol, natural gas processing, hydrogen production at oil refineries, steel facilities, and GTL plants) coupled with nearby geological storage make it possible to develop hubs, that can act as a nexus for CCUS and benefit from economies of scale. This study has identified ten promising hub locations with the most favourable being located in Jubail, Saudi Arabia; Northern Qatar, and Abu Dhabi. Cross border collaboration will allow isolated clusters to connect to hubs avoiding replication of CCUS infrastructure and provide opportunities for decarbonisation where there is no nearby storage in country.

The Value of CCUS in the GCC and the challenges

The GCC could realise significant economic benefits from decarbonisation as well as creating thousands of new jobs and protecting existing ones. Opportunities for the GCC associated with hydrogen export and CCUS could add $15-44bn in gross value added (GVA) to the GCC in 2050 and support between 87k-245k jobs, indirectly supporting hundreds of thousands more. The GCC is well placed to establish itself as a key producer and exporter of low-carbon hydrogen with a global market share of between 16% and 19% by 2050. Effective decarbonisation of industrial activity also enables the GCC to maximise its future oil and gas production and repurpose existing uses of oil and gas for export.

Since the GCC lacks a strong domestic driver for CCUS, a strong business model and incentive scheme will need to be deployed. A range of business models for CCUS have been developed around the world, but without government subsidy CCUS projects generally only work where there is a revenue stream from utilisation. Successful CCUS business models decouple value chain risk with separate models for capture, transport, storage and utilization. There needs to be an agreed carbon price, incentivization or penalty system in order to encourage CCUS deployment.

Executive Summary

How to unlock the full potential of CCUS in the GCC

CCUS costs can be expected to decrease by up to 43% in the GCC with a lower cost base compared to other regions. Capture technology cost reduction is expected to be global in nature based on 'learning by doing', economies of scale and reduced contingencies. Transport and storage cost reduction is expected to be local in nature based on inherent competitive advantage from project execution, geology, land and labour costs. Distance, volumes, option, storage site location and business model will be the biggest levers in realizing cost reduction for CCUS in the GCC. The GCC should support ongoing R&D, particularly with next generation technology and hard to abate sector capture tech, since this will bring cost savings forward and allow more efficient hubs to be developed.

The GCC has significant potential to become a global leader in low carbon hydrogen production and export of low carbon goods. In the long term green hydrogen production offers the best route for the GCC, based on natural endowments, but in the short term a twin track approach with blue and green hydrogen is recommended. Additional research is required for pyrolysis and oil to hydrogen pathways which could important to the GCC. Current regional demand and projected global demand supports a hydrogen industry, but there are also additional monetisation routes for low carbon derivatives such as ammonia, methanol and steel.

The GCC has good conditions for large scale deployment of DACCS in the long term, with BECCS meeting the short-term need. CCUS alone will not be sufficient to decarbonise the economies of the GCC and carbon removal technologies will be required. Beyond their use in impossible to abate sectors carbon removal technology will be required to stabilise global temperatures and address historic emissions by removing them from the atmosphere. DACCS is currently in early commercialisation but could prove cost effective in the GCC if the requirements for water are met. In addition DACCS can be used to manufacture zero carbon syn-fuels which are one potential solution to replacing aviation fuel.

The GCC needs to decide the pace of decarbonisation but there is a clear roadmap to 2030 that will need to be followed to set up for success. To realise the significant value offered by CCUS and hydrogen in the GCC, immediate action in the early 2020's is needed, including a detailed CO_2 storage appraisal, development of the first clusters and hub and deployment of the first transport and storage (T&S) infrastructure. From 2030 onwards the focus should be on scaling up to commerciality building on successful pilots and matching market demand with development. Over the longer term, economic reforms could unlock the potential for market mechanisms to deliver CCUS cost-effectively. Clear industrial policies linked to market demand should be developed so that the opportunities for internationally competitive sectors in low carbon goods is quantified. The roadmap is flexible to adapt to changing reality and there should be reflection at a number of points to measure progress against both internal goals and global targets. The focus should be on getting the path to 2030 right to set the decarbonisation agenda in the GCC on the right course. The GCC must choose early whether it wants to lead the CCUS and hydrogen agenda or respond to other states actions, choosing a slower path will likely lead to a lower market share for export products in low carbon and hydrogen but the market will be there.

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The GCC roadmap to 2035 is all about stakeholder engagement, partnerships, policy, pilots and a heavy focus on domestic roll out at scale

2022

Kick-off of CO_2 storage catalogue, policy reviews, market reviews and feasibility studies. Workshops and stakeholder engagements to agree GCC strategy and vision

2024

Storage studies and feasibility for pyrolysis and oil to hydrogen complete. FEED for first hub(s), hydrogen plants and backbone infrastructure

2026

Policies for CCUS and hydrogen in place. First hub(s) and low carbon hydrogen plants in operation, additional clusters in development

2030

Scale-up of CCUS and hydrogen with additional hubs, clusters and plants. Development of low carbon products for export (Ammonia, Steel, Methanol)

2035

Increasing pace of scale-up and connection of new hubs and sectors. All hydrogen production and natural gas processing should be blue or green

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CHAPTER 1

Introduction

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The GCC is home to some of the most energy and carbon intensive industries in the world making the journey to net zero challenging

- **The GCC countries depend heavily on oil and gas for energy supply and domestic consumption.**
  - The region's countries are rapidly growing energy consumers, a product of the growth in gross domestic product (GDP), population, and the pressures of urbanization. The GCC accounts for circa 25% of global crude oil production (BP 2021), mostly from Saudi Arabia, the UAE and Kuwait, with these countries among the world’s ten-largest crude oil producers in 2017. The GCC is also home to most of the world’s spare production capacity (IRENA, 2019).
- **Historically, most of the GCC states’ oil production has been exported, owing to high reserves and comparably small domestic consumption.**
  - Although the region’s domestic energy demand has risen tremendously in recent years, the GCC is the source of just under a third of the crude oil supplied to the international market and accounts for more than two-thirds of the Middle East region’s exports of crude oil. More than half of the GCC exports come from Saudi Arabia, although the country, together with Kuwait, still use crude oil and oil products for power generation, as natural gas supplies have lagged behind growth in peak demand (S&P Global Platts, 2018).
- **Rising awareness of environmental issues across the GCC and the need to reduce domestic energy consumption and CO_2 emissions have risen to the top of political agendas.**
  - The region is engaged with being part of the energy transition, rather than being staunchly opposed. Since 2010, countries in the region have been engaging in an incremental process of energy pricing reconfiguration, promulgation of energy efficiency policies, and national strategies to reduce their domestic carbon emissions. Many of the GCC countries have pledged net zero strategies which include CCUS and hydrogen as part of their updated Nationally Determined Contribution (NDC) to the Paris Agreement, with an ultimate target to achieve economic diversification away from oil and gas exports with climate mitigation co-benefits.

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In most future net zero scenarios CCUS is envisaged and for the GCC there are domestic benefits too

GLOBAL NEED FOR CCUS

– **CCUS will be required under all scenarios if global climate goal targets are to be met by 2050 and beyond in a cost-effective manner.** Almost all the IPCC scenarios involve CCUS, with the cost of following decarbonisation without carbon capture and storage estimated at greater than $4 trillion (IEA) globally. With a greater focus on low carbon hydrogen to kick-start the hydrogen economy, which will require CCS at scale, and the desire to fully decarbonize energy intensive industry by many countries, the need for a comprehensive CCUS strategy is clear.

– **Domestic CCUS deployment could help the GCC states decarbonize their economies, supporting emissions reductions pledges under their NDC’s.** The GCC countries could be emitting up to 700Mt CO_2/yr by 2050 based on AFRY projections of domestic industrial emissions growth. Capturing a significant percentage of these emissions is crucial to meet targets under GCC NDC’s. In the short term, domestic energy consumption and emissions are rising rapidly, although recent policies and the slow uptake of renewables are beginning to slow this growth. Saudi Arabia, UAE and Oman are already developing expertise across the CCUS value chain, as well as driving international collaboration in CCUS. With appropriate public and private sector backing, the first GCC CCUS hub could be operational by 2025, soon followed by other industrial hubs.

ECONOMIC BENEFITS TO THE GCC

– **CCUS also has the potential to drive a number of the economic aims of the GCC, such as economic diversification and sustainable development**. The GCC economies are heavily dependent on oil and gas exports, yet all share a desire to diversify to varying degrees. CCUS would help protect existing high value jobs and unlock several export opportunities, including clean hydrogen and additional low carbon products such as petrochemicals or steel. With its huge geological potential, the GCC can pursue Carbon Capture as a Service (CCaaS) for neighboring countries to help them on their decarbonization journeys.

– **Global deployment of CCUS is strategically important for the GCC, as it has the potential to reduce global oil and gas demand erosion while meeting world climate targets.**

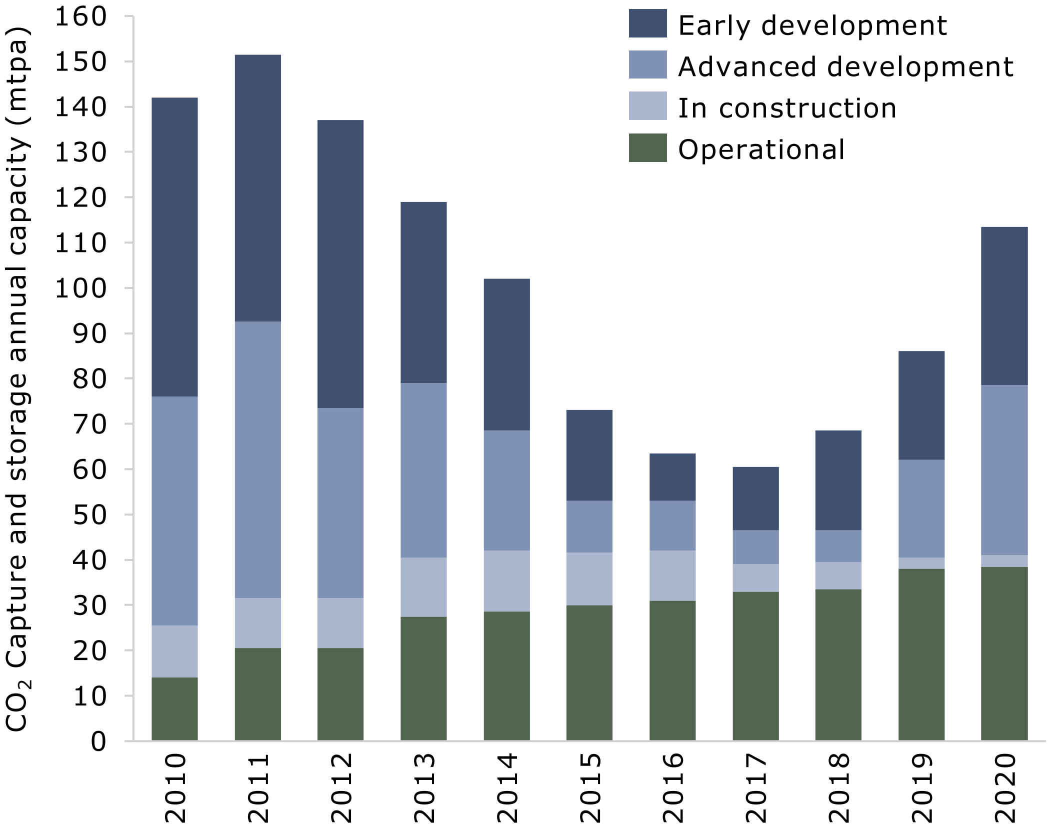
– We estimate new market opportunities in hydrogen export and CO_2 storage services could add **US$15.5bn** to **44bn** in gross value added (GVA) to the GCC in 2050 and support between **87,300** and **245,400** jobs (directly and in the wider economy)

Globally there is extensive development of CCUS ongoing, including in the GCC

OPERATIONAL COMMERCIAL-SCALE CCUS FACILITIES

29 existing operational CCUS projects across the globe but with a strong concentration in North America, storing ~40mtCO_2 per annum

CHART OF CCUS DEVELOPMENT GLOBALLY*



Source: Global CCS Institute; *The capacity of facilities where operation is currently suspended is not included in the 2020 data

The OGCI has requested that AFRY and Gaffney Cline conduct an in-depth study into the future role of CCUS in the GCC

COMMENTARY

- The Oil and Gas Climate Initiative ("OGCI"), launched in 2014, is a voluntary, CEO-led initiative which aims to drive the industry response to climate change. Active member companies are BP, Chevron, CNPC, Eni, Equinor, ExxonMobil, Occidental, Petrobras, Repsol, Saudi Aramco, Shell and Total.
- The OGCI CCUS Workstream aims to facilitate the emergence of a commercially viable, safe and environmentally responsible CCUS industry that can contribute at the scale needed to help meet the aims of the Paris Agreement.
- In 2019, OGCI commissioned a white paper study on CCUS in Saudi Arabia, focused on the value and opportunity for deployment. This report represents a second study phase, building on the methodology and findings of the Saudi CCUS white paper to expand to other Gulf countries (UAE, Qatar, Bahrain, Kuwait, and Oman).
- In particular this report seeks to further strengthen the CCUS values for the region, identify cross-border deployment opportunities, and catalyse collaboration among GCC countries with an aim to ease and accelerate deployment.
- The findings of this study will be presented to an audience of national stakeholders, including senior executives in both governments and industrial companies.

STUDY OBJECTIVES

- Assess the value of CCUS for each of the Gulf countries (UAE, Qatar, Bahrain, Kuwait, and Oman) including the role of CCUS in mitigating long term oil market erosion for each country and helping each country meets its medium- and long-term strategic goals.
- Identify CO_2 source concentrations proximate to nearest storage site across the region.
- Identify opportunity for shared infrastructure within countries and cross border opportunities with a view of establishing a GCC CCUS hub.
- Identify or design enabling mechanisms that support a vision for a CCUS industry in the Gulf.
- Recommend a roadmap with milestones, for CCUS deployment in the region, leveraging CO_2 transport and storage synergies.
- Identify potential for low carbon product market development.

Our project has four workstreams to assess the value of CCUS for Gulf economies and identify business models, technologies, and infrastructure needs

1

Workstream 1: Carbon sources and sinks

CO_2 Sources analysis
Atlas of CO_2 storage fairways & capacity

2

Workstream 2: Potentials and opportunities

Business models, Cost reductions, hydrogen, hub analysis, carbon removals

3

Workstream 3: Macroeconomic analysis

Multiple scenarios analysing the impact of CCUS penetration on oil and gas use, investment impact of CCUS, and socio-economic value generation

4

Workstream 4: Roadmap creation

Recommendations on a potential roadmap for regional CCUS deployment, with milestones

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To achieve the objectives of this study a step-by-step approach was taken to evaluate the opportunities and formulate a CCUS roadmap for the GCC

- The remainder of this chapter summarises the findings for each of the workstreams. The report is structured into 9 chapters as follows:
  - **Chapter 2** details the carbon sources in the GCC and their geographic distribution.
  - **Chapter 3** highlights the main carbon sinks where CO_2 could be stored and presents the relative volumes of storage available to the GCC
  - **Chapter 4** highlights potential locations for hubs in the GCC and the feasibility for developing them
  - **Chapter 5** presents the main values of large-scale CCUS deployment to the GCC and the economic benefits of realising this value in terms of growth, jobs created and export opportunities.
  - **Chapter 6** considers the possible business models that could enable more rapid roll out of CCUS in the GCC
  - **Chapter 7** presents the opportunities for cost reduction in deployment of CCUS across the GCC.
  - **Chapter 8** considers the role of hydrogen in the GCC and the opportunity for production and export.
  - **Chapter 9** highlights the opportunity for carbon removals, considering BECCS and DACCS and how they fit in with the GCC decarbonization journey.
  - **Chapter 10** details the roadmap deployment strategy for large-scale CCUS in the GCC. It includes a 1-page overall deployment strategy, the details of physical infrastructure deployment and key enabling actions needed to realise CCUS value for the GCC.
- The report concludes with a summary of the conclusions and a Technical Appendix section providing more analysis on individual industrial clusters, carbon sinks, hydrogen, a summary of key assumptions that guided the modelling, and references.

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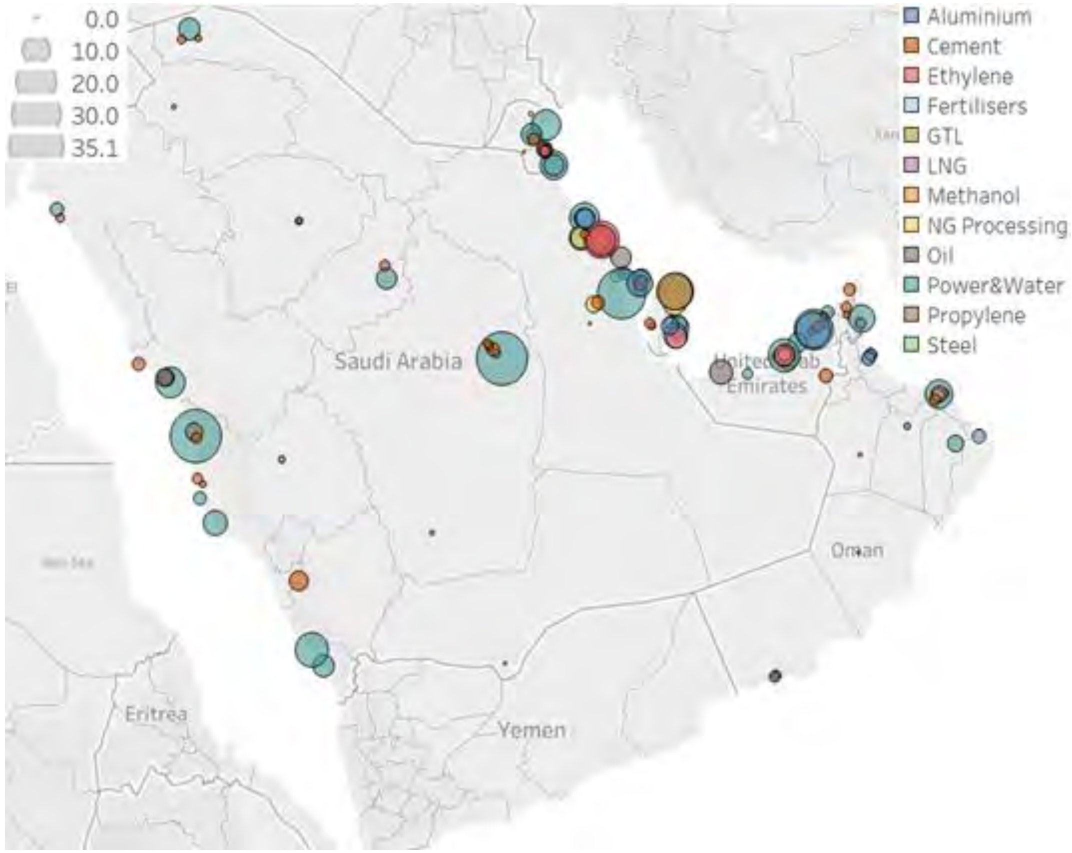
The GCC has abundant sources of CO_2 for abatement which are mainly organised into clusters favouring CCUS

CARBON EMISSIONS POINT SOURCES

- Saudi Arabia and the UAE account for more than 60% of GCC CO_2 emissions driven by the high activity of their oil refineries, petrochemical plants, and power sectors. Qatar's expanding LNG, petrochemicals and aluminium sector will see it join the high emissions club
- Electricity generation and desalination in the GCC has the highest CO_2 emissions due to the extensive use of oil and natural gas. After power generation petrochemicals, oil/fuel refining, and aluminium sectors are the main CO_2 emitters. Despite reductions in emission intensities across the various industries, CO_2 emissions continue to increase due to population growth and expansion of production capacity to meet domestic and global demand
- CCUS is technically and economically more suitable for industries characterised by high purity CO_2 streams which result from the ease of separation of CO_2 from other gases and impurities in flue streams. These industries include natural gas processing, petrochemicals, fertilisers, methanol, and to a lesser extent aluminium, steel and oil refining
- Whilst being the main contributor to CO_2 emissions, the application of CCUS in the power sector will be more challenging because of cost and contractual agreements in place.

MAP OF CO_2 CAPTURE POINT SOURCES IN THE GCC



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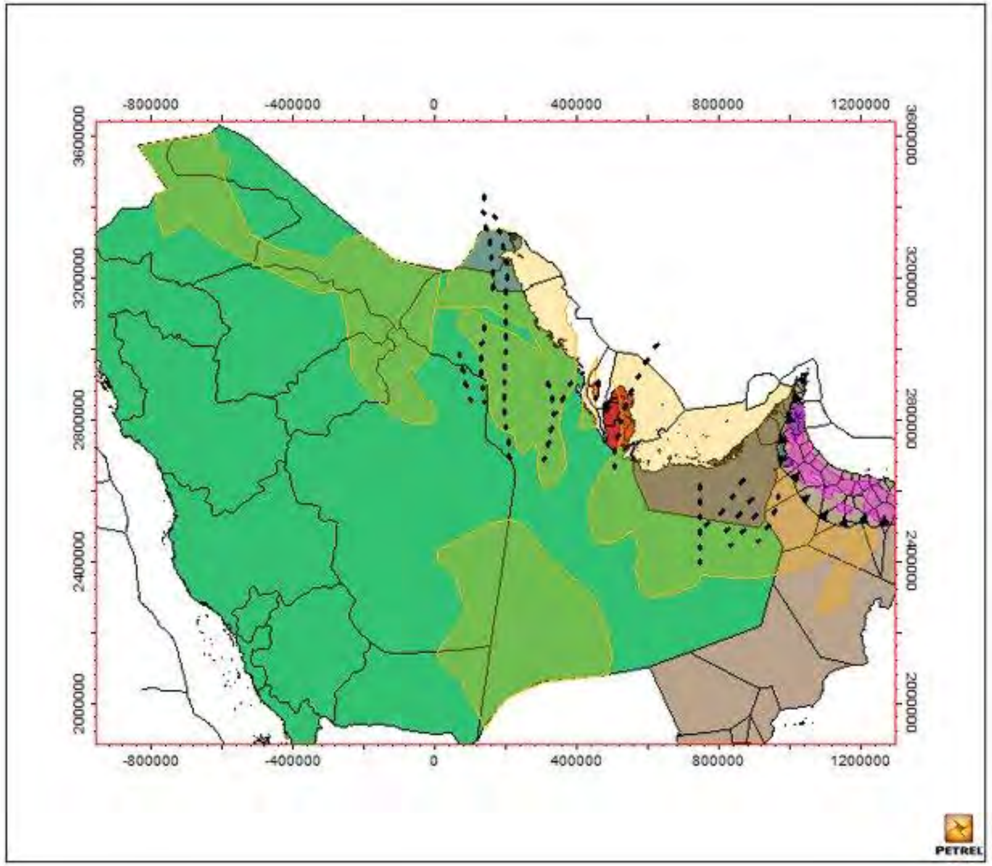
Geologically the GCC is well placed for world class storage reservoirs but will need more detailed work to identify individual opportunities

STORAGE OPPORTUNITY IN A RANGE OF SETTINGS

- The GCC has significant geological storage potential in both depleted oil and gas reservoirs and saline aquifers close to emissions clusters, with opportunity across 11 sedimentary sequences and the Oman ophiolite
- Storage density is highest in the Rub'al-Khali basin and Kuwait, with the former offering the most diverse range of available plays in the GCC as a whole
- Risks are optimal in well-sealed sandstones and shallow carbonates with proven reservoir trends, poorest risks are in deep, tight carbonates where injectivity and reservoir distribution are unknowns
- The Oman ophiolite offers uncertain efficiency but large potential volumes and a different route to storage via mineralization – but will need further study
- Based on the analysis conducted in this study, the estimated Total Best Case storage volume in saline aquifers and ophiolite is 127.5Gt of CO_2, and a further 41.5Gt of CO_2 in depleted gas fields (over 230 years storage of GCC emissions at current levels)
- The GCC is technically competitive with other attractive regions of the world with respect to storage presence, quality and volumes, but detailed studies will be needed to delineate opportunities and appraise their storage volume

MAP OF GEOLOGICAL STORAGE PLAY FAIRWAYS IN THE GCC



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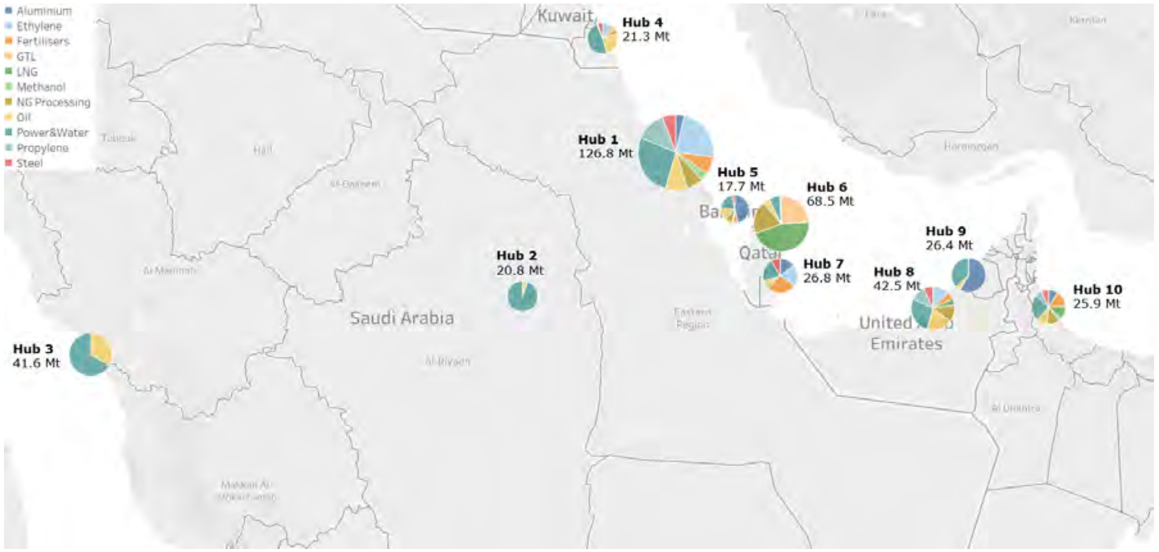
Eight potential hub locations have been identified that could support regional demand, but will require a detailed subsurface evaluation to rank them

HUBS BENEFIT FROM ECONOMIES OF SCALE

- The GCC region has many sources of high purity CO_2 streams which could be easily captured at low costs
- These sources include some of the biggest industries in the GCC such as petrochemicals, fertilisers, methanol, natural gas processing, and future hydrogen production
- The sources are located close to geological sinks which are stacked in the Rub'al-Khali basin giving Saudi Arabia and UAE a competitive advantage in terms of CO_2 storage capacities
- Longer term across the GCC depleted oil and gas reservoirs and the Oman Ophiolite offer additional storage opportunities close to large sources
- Saudi Arabia and UAE are already advanced with plans for hubs which match with hubs identified in this study (Jubail and Abu Dhabi)
- Bahrain and Kuwait have lower emissions than other GCC member states due to the lower industrial activity and population, however, their emissions could be clustered with those of Jubail or Qatar making them active participants in the CCUS market

IDENTIFIED HUBS ACROSS THE GCC



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The current primary incentive to install CCS in the GCC is EOR – a strong policy and support environment is required to make CCUS more widespread

CCUS AT SCALE WILL REQUIRE A COMMERCIAL DRIVER

- The GCC region already has four CCUS projects but deploying CCUS at scale will require a commercial driver.
- In the GCC, as globally, Enhanced Oil Recovery (EOR) has been the strongest commercial driver for carbon capture and storage, although a number of new business models are emerging which are looking to significantly accelerate deployment.
- The GCC lacks a strong commercial driver for domestic decarbonisation (e.g., a carbon price or emission limits), but there is significant ambition to bring forward CCUS as part of a circular carbon economy with government subsidy being considered as well as carbon market mechanisms
- CCUS policies vary around the world and it will be important to select the right mix to incentivise and accelerate deployment
- Getting the ownership structure, revenue streams and incentive structures right can help CCUS to develop successfully, opening up economies of scale from sharing common infrastructure between different capture projects and across borders. Unsuitable business models can increase costs and result in less or no CCUS development.

POTENTIAL DRIVERS FOR CCUS

Current primary commercial drivers for CCUS (global)

- EOR-led CO_2 utilisation
- Regulatory emission restrictions
- Direct grants to CCUS projects
- Direct capture subsidies
- Emission costs (carbon price)
- Storage subsidy (e.g. tax credit)

Possible new primary commercial drivers for CCUS

- Carbon border adjustments on exports
- CO_2 capture obligation on industry
- CO_2 storage obligation

Secondary drivers for CCUS

- Non-EOR CO_2 utilisation
- Corporate Decarbonisation & Image

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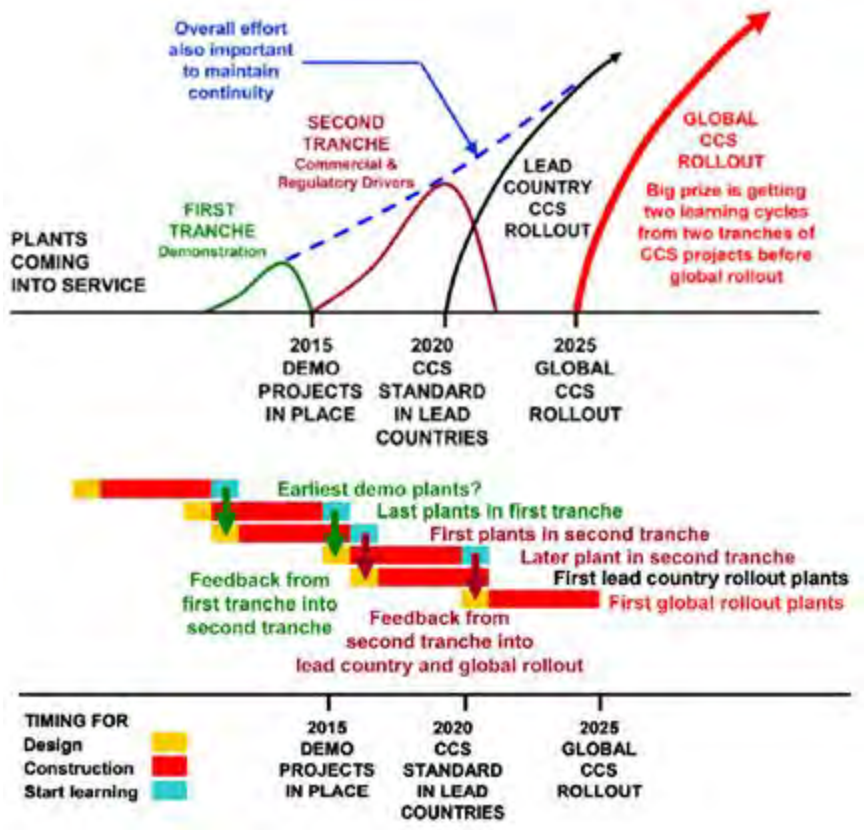
Significant cost reductions can be expected in the GCC as CCUS technology is deployed with a reduction of up to 40 percent by 2050

LOW-COST BASE AND RAPID LEARNING TO 2030

- With the right support significant cost reductions can be expected in the GCC based on excellent storage resource, strong operational experience with gas handling as well as low land costs, low labour costs and a potentially attractive CCUS investment environment
- Diverse CO_2 capture projects, coupled with extensive potential capture sites means that there should be rapid capture of economies of scale and allows for learning on deployment of successive generations of projects
- However, we do expect some barriers to the rapid roll-out of low cost CCUS such as the lack of an existing policy framework in the GCC relating to CCUS and carbon emissions
- Capture cost evolution to the early 2030s show rapid cost declines as the transport and storage network expands and new generations of projects benefit directly from cost discovery and learning from previous generations
- Beyond 2030 cost decline expected to slow as cost savings become incremental as seen from learning rates of a range of industrial benchmark technologies in the last 30 years
- Overall costs are expected to reduce by 40% from 2025 to 2050

COST REDUCTION THROUGH LEARNING CYCLES



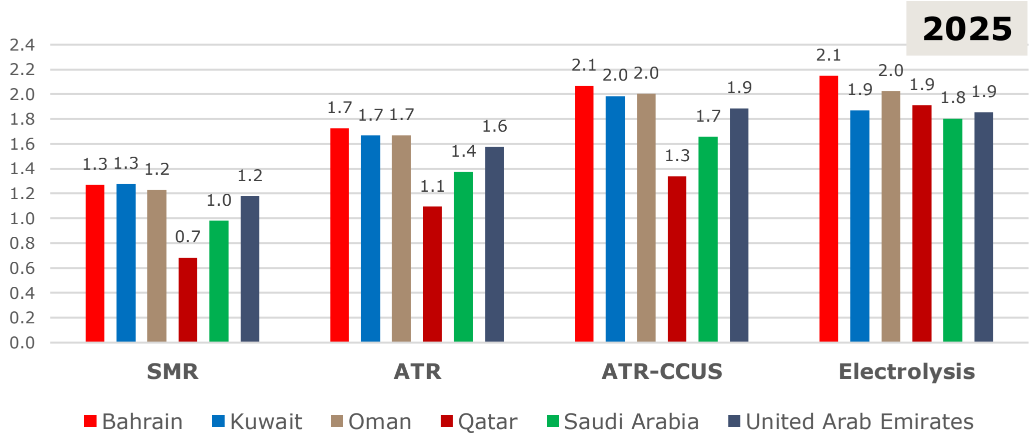
Source: Preparing for global rollout, J.Gibbins, H.Chalmers, Energy Policy, 36, (2008), 501 – 507

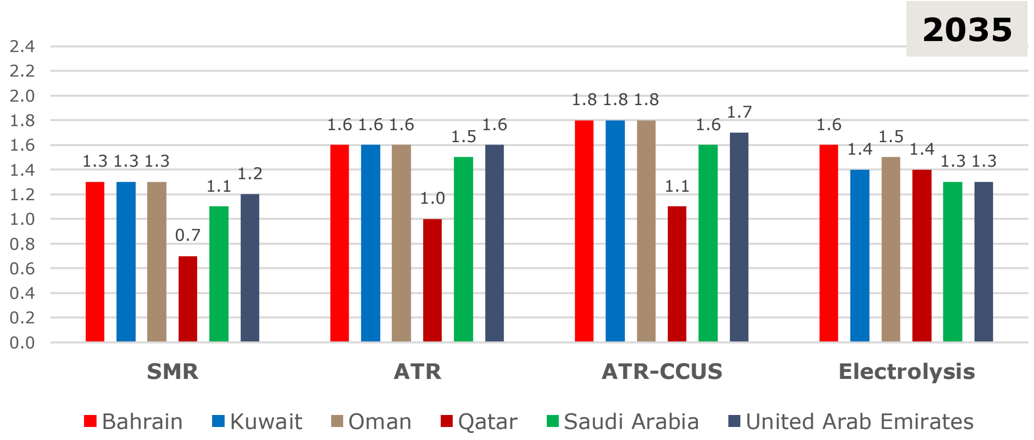
Sufficient resources exist in the GCC to support a twin track approach to hydrogen, but will require strong policy and subsidy support initially

HYDROGEN IS AN OPPORTUNITY FOR THE GCC

- Due to natural endowments the GCC can follow a twin track approach to hydrogen production, although in the long term green hydrogen production is most cost-effective
- Pyrolysis and carbon black could launch whole new industries in the region as well as satisfy current demand and offers an alternative to blue and green production – but further research and demonstration will be needed
- Opportunity is not spread evenly and individual state hydrogen road maps need to be pragmatic and encourage collaboration rather than competition
- Ammonia currently offers the best at scale transport option based on cost and versatility, but the lack of pipeline routes to key markets will require expansion and adaption of shipping and target of closer regional markets to cement competitive position
- Current regional demand and projected global demand supports the establishment of a hydrogen industry, with a large market for hydrogen and low carbon derivatives such as ammonia and steel
- Competition from other countries means that risks will need to be taken to secure market share, but exports will not compensate for lost oil revenues

LEVELISED COST OF HYDROGEN - $/KG,H2





GCC well placed for large scale DACCS deployment with the potential to produce carbon neutral e-fuel

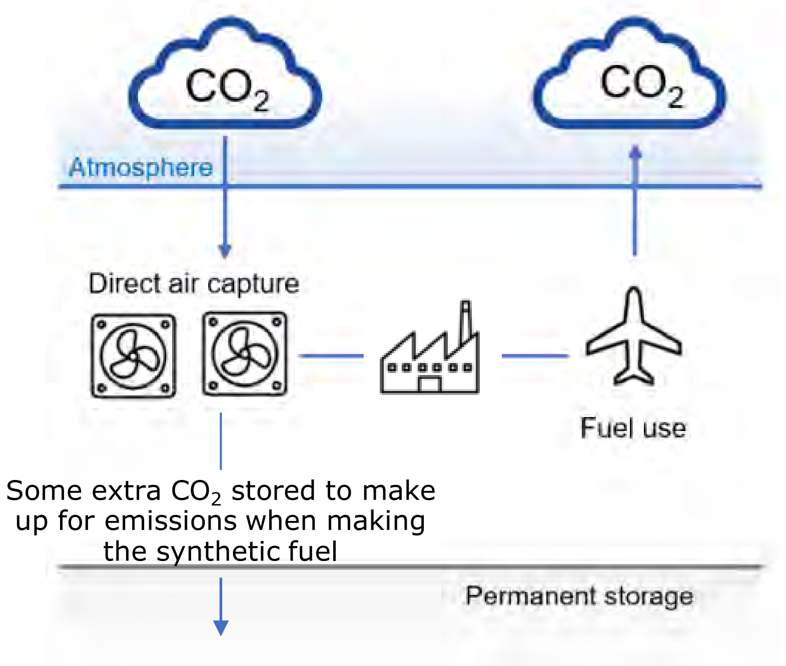
FOR NET ZERO CARBON REMOVAL WILL BE REQUIRED

- Carbon capture alone will not be sufficient for decarbonisation and technologies that remove carbon from the atmosphere are needed
- There are a number of carbon removal technologies, but BECCS and DACCS offer the greatest promise due to the near permanent duration of geological storage
- Whilst BECCS has long term sustainability concerns, DACCS cost is dependent on access to cheap clean energy source, carbon storage, and water
- DACCS could be cheaper in the GCC region, providing water requirements can be met
- The benefits of carbon removals are the possibility to make carbon neutral fuels especially when combined with a broader decarbonisation plan
- This could mean that oil and gas production could continue for longer in the GCC as carbon neutral production

DACCS CAN BE USED TO MAKE A CARBON NEUTRAL E-FUEL

- CO_2 captured from atmosphere ☑
- CO_2 captured = CO_2 emitted ☑

Carbon neutral



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By decarbonising the GCC economies through CCUS, Hydrogen and DACCS GVA up to $44 billion can be added, supporting 245k new jobs

THE OPPORTUNITIES

- We estimate new market opportunities in hydrogen export and CO_2 storage services could add **US$15.5bn** to **44bn** in gross value added (GVA) to the GCC in 2050 and support between **87,300** and **245,400** jobs (directly and in the wider economy)
  - As global hydrogen demand increases in response to pressures for decarbonisation, the GCC is well placed to establish itself as a key producer and exporter of low-carbon hydrogen with a global market share of between **16% and 19% by 2050**
  - The export revenues associated with this new export market would be between **US$50bn and 140bn** in 2050 contributing **US$15bn – 42bn in value added** and supporting **86,000 to 242,000 jobs**
  - The CO_2 storage hub developments will provide an opportunity to offer storage services for imported CO_2. in 2050, if 50 Mt/yr of imported CO_2 is stored (around 5% of domestic capture levels), revenues may be in the range of **US$500m to 2bn** in 2050, contributing **US$300m to 1.2bn** in value added and supporting **1,300 to 3,400 jobs** across the economy

NEW JOBS AND EXISTING JOB PROTECTION

- Domestic CCUS deployment would see around **US$180bn of investment** in capture, transport and storage infrastructure by 2050.
- The manufacture, construction, operation and maintenance of this CCUS infrastructure would directly support around **30,000 jobs**
- Without deployment of CCUS and Hydrogen, economic activity in the main industrial sectors would be unsustainable. By investing in CCUS and hydrogen, the GCC will **protect employment and income** in those sectors.
- Effective decarbonisation of industrial activity also enables the GCC to maximise its future oil and gas production

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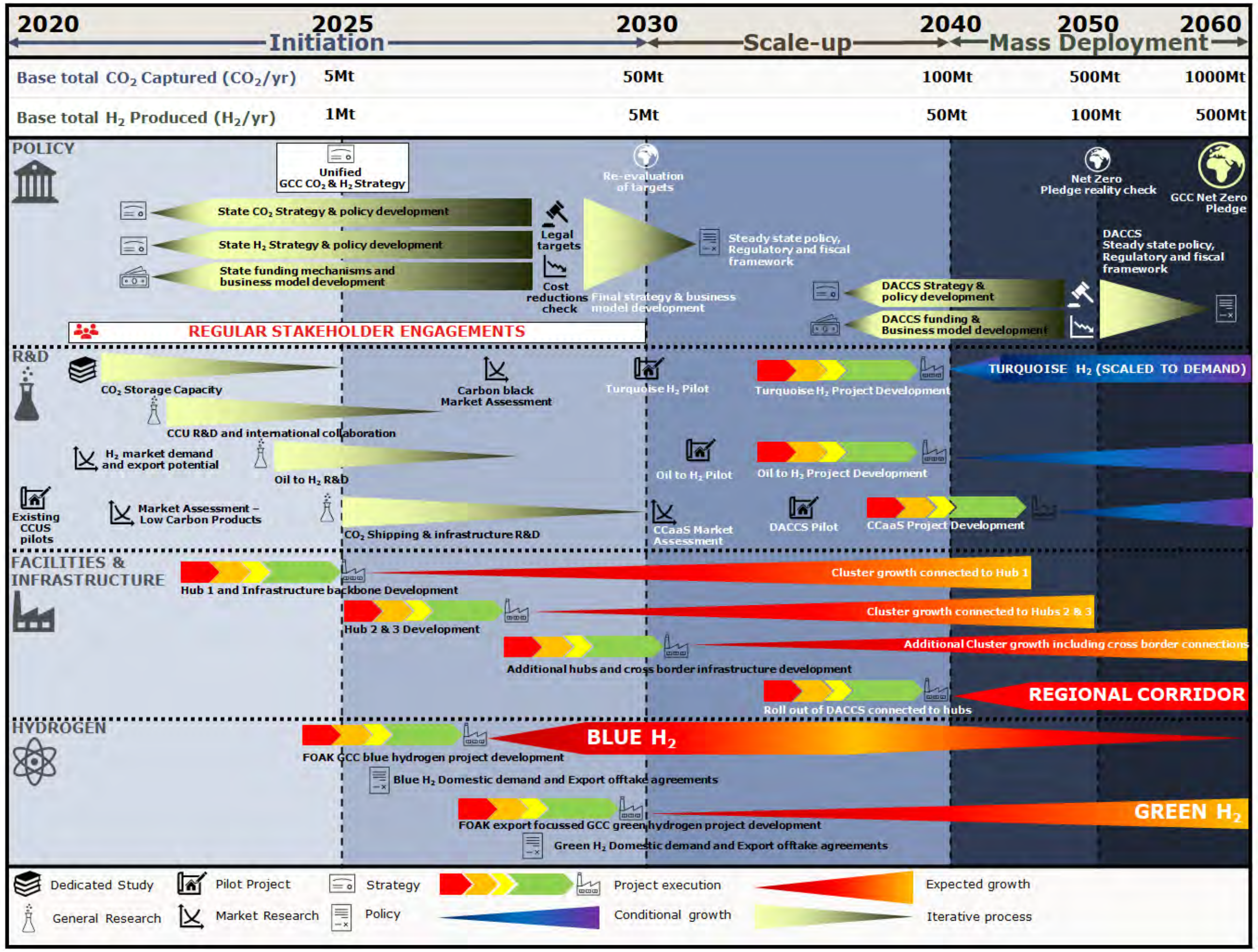
To realise this value clear policy, regulation and support are needed in the short and medium term



GCC CCUS & HYDROGEN OPPORTUNITY ROADMAP

- The goal of the GCC countries should be to maximize benefits from their natural endowments, deliver on climate ambitions, and protect existing jobs whilst providing opportunity for growth of new ones - global leadership on CCUS and hydrogen allows that to happen
- Early mover advantage will mean having the knowledge and experience to export to other countries as they start their decarbonisation journeys, as well as providing a low carbon industrial base that has competitive advantage for more eco-conscious countries and customers and becoming a global powerhouse for hydrogen production and export
- Companies in the GCC are already acting and a pipeline of projects are ready to deploy but there are strategic choices that must be made now as well as a comprehensive policy framework to give confidence to business and investors that their returns will be realised and the GCC is committed to a course of action

CHAPTER 2

Carbon Sources

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CCUS will play a central role in the decarbonisation of hard-to-abate industries in the GCC region

- Over the past decade, GCC countries have focused on the decarbonisation of their industrial activities through the adoption of cleaner fuels, the incorporation of energy efficiency measures, and the integration of renewables in their domestic energy mix. The roll-out of these measures has proven effective but rapid scaling up is needed if GCC states are to comply with their Nationally Determined Contributions. CCUS is expected to become one of the pivotal technologies in the GCC countries' quest to reduce their GHG footprint and meet their sustainability targets.

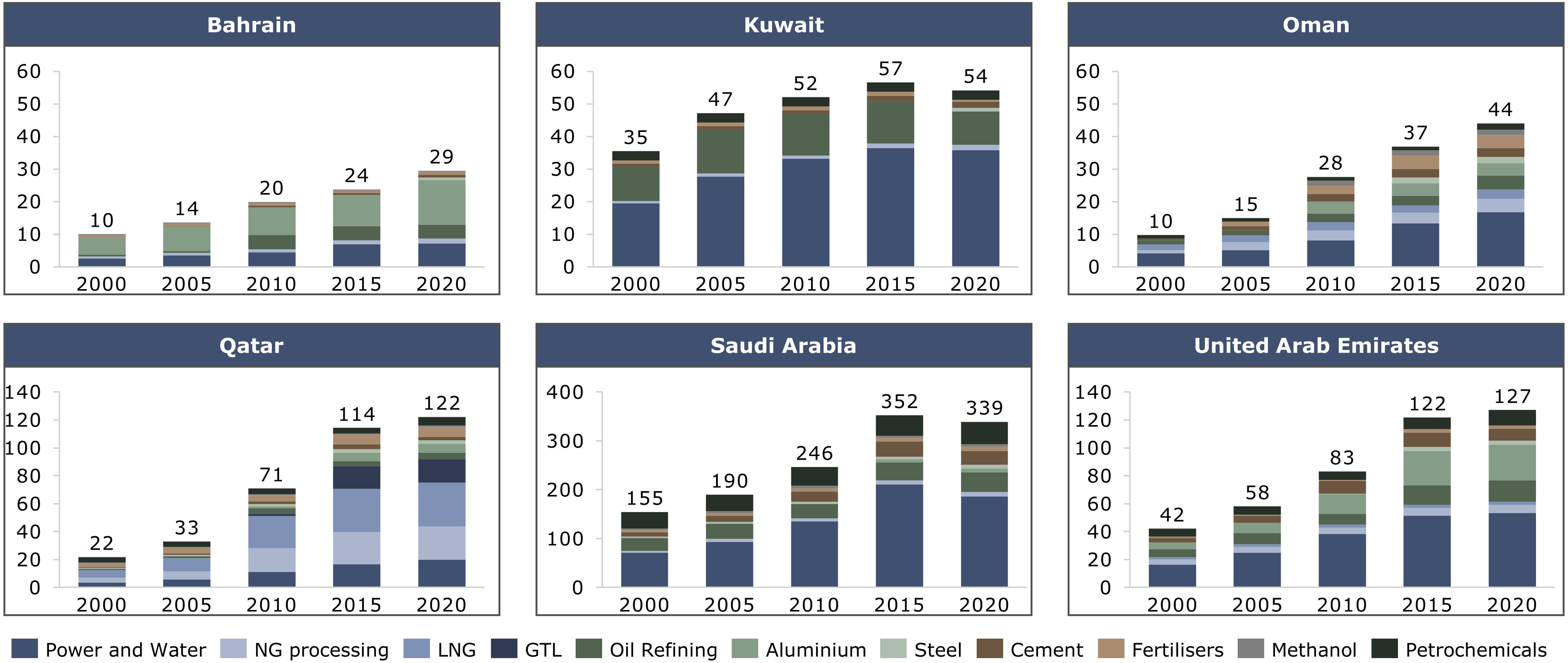
- The week before COP26 witnessed three net-zero pledges by the UAE, Saudi Arabia, and Bahrain. Oman is currently considering implementing a target of net zero by 2050. Thus, coupled with the roll-out of renewables and the utilisation of hydrogen, the deployment of CCUS will play a critical role in reducing CO_2 emissions in the GCC.

- The extent to which CCUS can be applied to a certain industrial activity depends on several factors and differs from one industry to another.

- Do future CO_2 emissions in the GCC region encourage the adoption of CCUS? And which industries could benefit the most from this technology?

- The GCC region has a rapidly growing industrial sector, flourishing oil and gas industry, and rising population. These indicators imply that energy consumption will continue to increase in the foreseeable future and CCUS technologies could be utilised to reduce carbon footprint of industries that produce high purity streams of CO_2

Historically Saudi Arabia and the UAE accounted for more than 60% of the GCC's industrial CO_2 emissions* – (Mt, 2000-2020)



Sources: AFRY Analysis, GlobalData, USGS, IAI ; * CO_2 emissions exclude transport and other non-energy use activities

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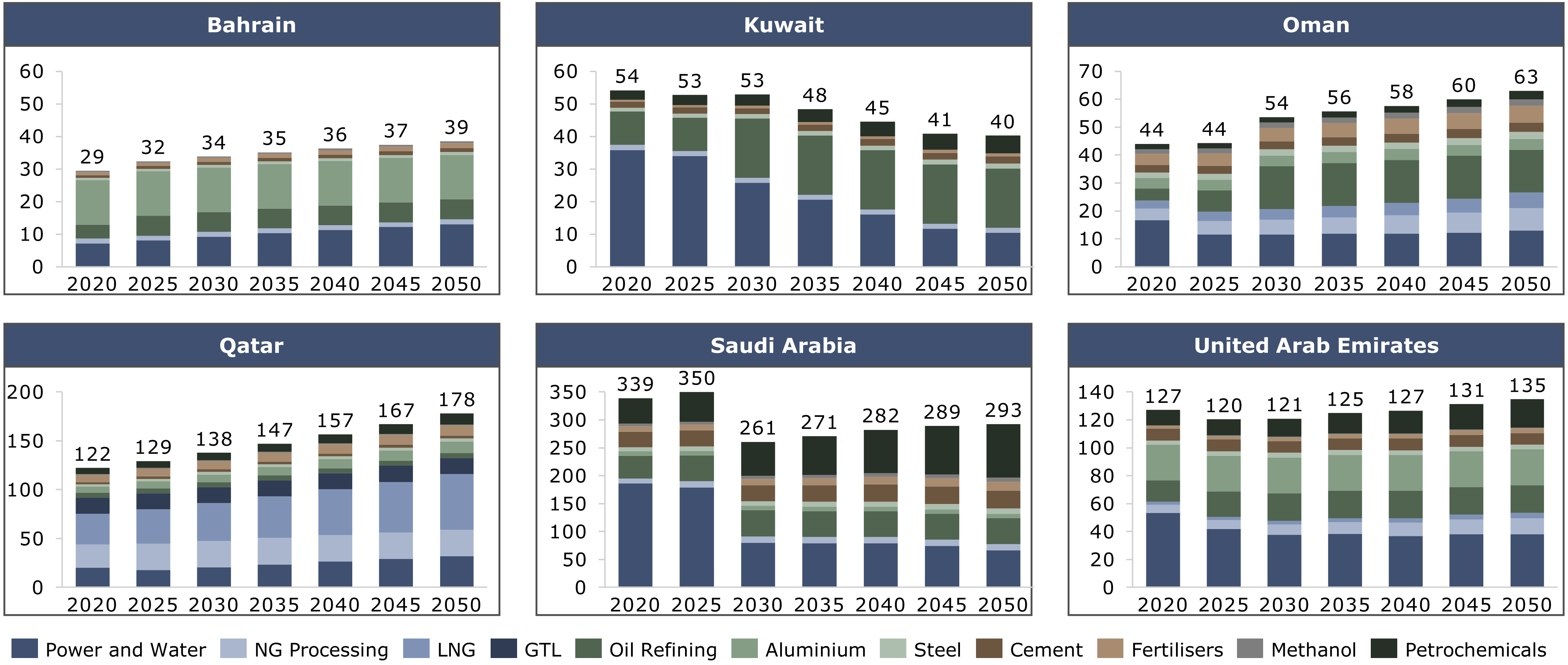
Transitioning to gas for power and increasing renewables is expected to reduce sectoral industrial emissions although there is cumulative growth



KSA emissions declined due to reduction of in country cement production and increase in gas power generation, after a decline due to Covid-19 an economic rebound is expected before further declines under KSA NDC pledges.

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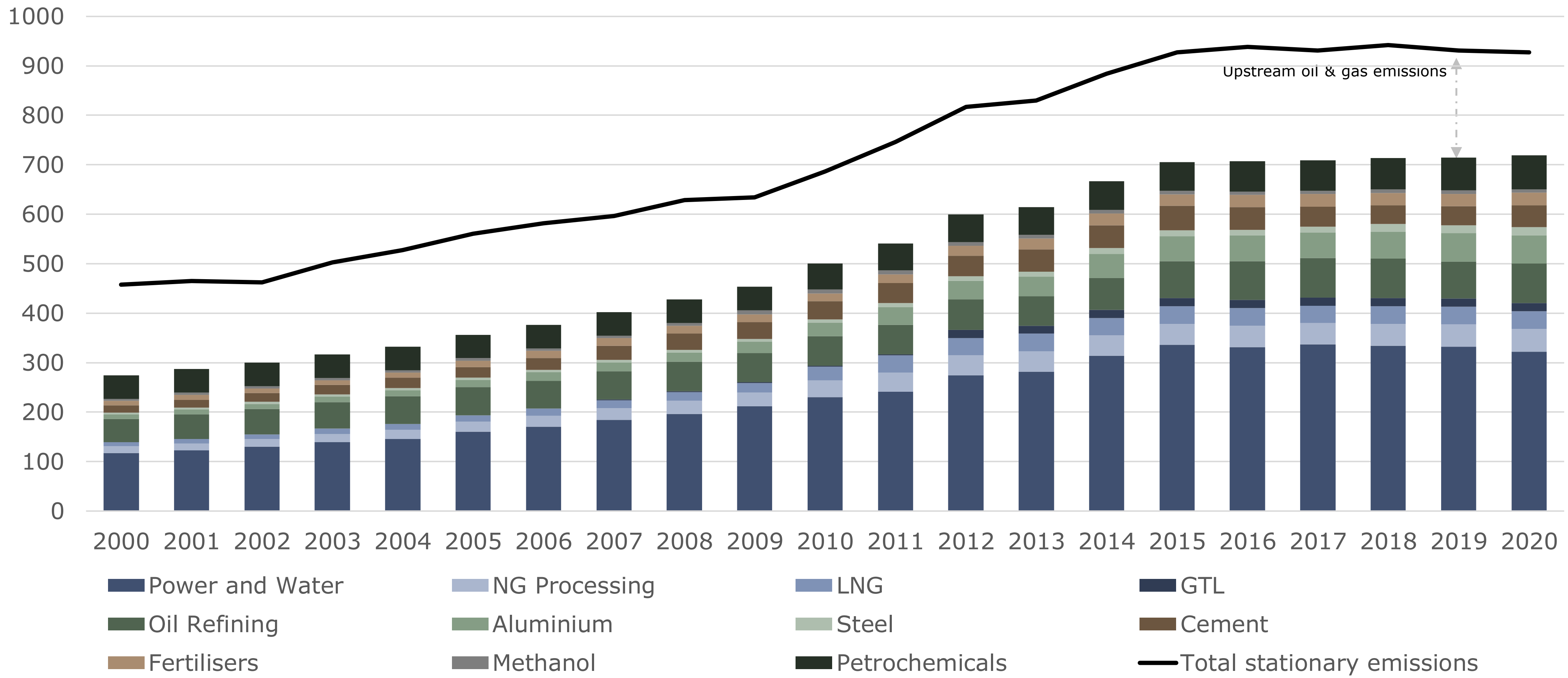
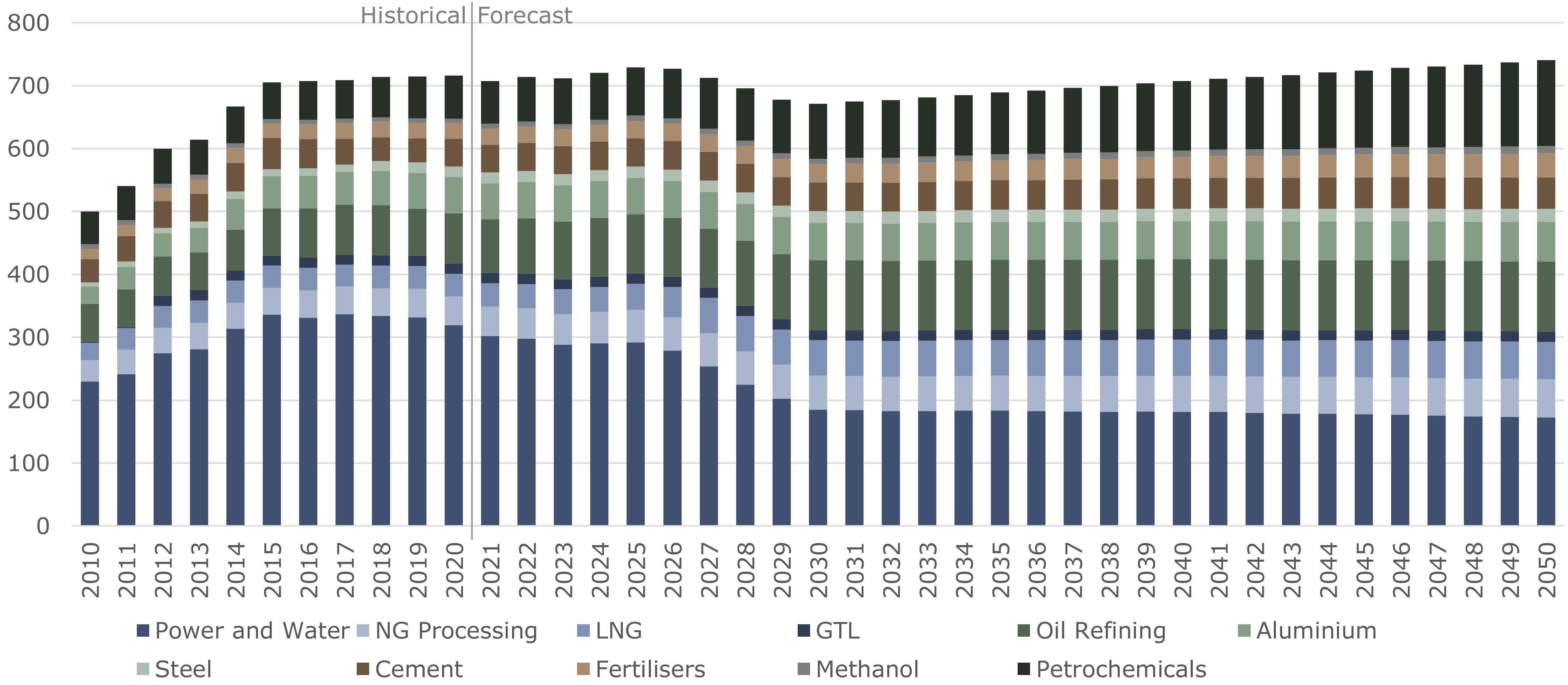
Across the whole GCC historical industrial CO_2 emissions grew across all industries but were largely driven by the power sector (Mt, 2000-2020)



Upstream emissions stem from multiple operations (drilling, production, processing, transport to refinery) but the most notable sources are venting, flaring, and fugitive emissions. Upstream emissions were excluded from our industrial emissions and hence are shown separately.)

Forecasts for increasing emissions are an opportunity to deploy CCUS at scale as part of the GCC's decarbonisation commitments (Mt, 2010-2050)



Note: 2020 data includes forecast data where historical data is unavailable

CCUS is technically and economically more feasible in industries that produce high purity CO_2 streams or realise high levels of autonomy

Fertilisers, Methanol & Petrochemicals

- CO_2 capture is cheap and simple due to the high concentration of CO_2 in flue streams and the lack of alternatives
  - Fertiliser plants ~ 97% CO_2 concentration
  - Methanol plants ~ 99% CO_2 concentration
  - Petrochemicals ~ 100% CO_2 concentration
- On-site CCUS could face competition from other blue and green hydrogen sources

Oil Refining and NG processing

- Oil refineries utilise hydrogen produced by on-site SMR units for hydrocracking and desulphurization. Hydrogen production produces high purity flue streams containing 45% of CO_2 making the SMR fraction of emissions relatively easy to capture. The complete decarbonisation is challenging due to numerous small emissions sources
- Natural gas processing involves the removal of impurities like CO_2 and H_2S from natural gas reservoirs to comply with end-user specifications and avoid corrosion. High-concentration CO_2 streams resulting from the separation process makes gas processing one of the easiest and lowest cost applications of CCS at the natural gas processing stage

Steel

- GCC steel facilities are all gas-based DRI plants that utilize either Midrex or the Energiron technology. The majority of emissions occur during iron ore reduction in the shaft furnace
- Some cheap capture streams but capture from all CO_2 streams is challenging
- Al Reyadah CCUS facility in Abu Dhabi is the world's first commercial retrofit CCS in the iron and steel industry

Aluminium

- Captive power generation is the primary source of CO_2 emissions in aluminium smelting contributing to more than 60% of emissions while the remaining portion comes from process emissions
- Captive power plants could be retrofitted with CCUS at medium cost
- Process emissions are 1% by volume and are harder to capture due to the low CO_2 concentrations

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The application of CCUS in other industries could be more challenging but is still possible

Electricity Generation

- Natural gas turbines produce very dilute flue streams containing 4-6% of CO_2, hence the power sector is a medium capture cost sector
- The IPP model in the GCC imposes contractual difficulties to retrofitting existing power plants with CCUS
- Despite these considerations, exploring CCUS opportunities in the power sector is essential to meet decarbonization targets due to the substantial CO_2 emissions from this sector
- Only two existing power plants were retrofitted with CCUS – Petra Nova in Texas and Boundary Dam in Canada

Cement

- Cement plants produce dilute flue streams with CO_2 concentrations in the range of 22%
- Two-thirds of CO_2 emissions are process emissions from the calcination process
- Considered a high capture cost sector but new technologies like LEILAC could reduce these costs significantly

LNG

- Natural gas is combusted to power refrigeration compressors and electrical generators making the application of CCUS in LNG plants similar to that in power plants
- Produces less purity CO_2 streams than in natural gas processing
- Qatargas LNG CCS project captures 2.1 Mtpa of CO_2 and is expected to expand to 5 Mtpa by 2025

GTL

- GTL plants consume large amounts of hydrogen (approximately 70% of Qatar's hydrogen production is consumed by GTL plants)
- Hydrogen production produces high purity streams containing 45% of CO_2 making the SMR fraction of emissions relatively easy to capture
- Limited investigation of other point emitters due to the small number of plants globally

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Contents

Carbon capture can be applied to any process that emits CO_2 – but some sources are easier to capture than others

Carbon capture, combined with utilisation or storage, can be applied to any process that emits CO_2. However, non-stationary sources (i.e. transport) carry extensive challenges, and some stationary sources are significantly easier to capture CO_2 from than others.

In this section we look at CO_2 levels associated with the most likely applications for fitting carbon capture in the GCC:

- Electricity generation
- Oil & gas activities (specifically refining, natural gas processing, and natural gas liquefaction and gas to liquids plants)
- Metals production (specifically aluminium and iron & steel)
- Cement
- Chemical production (specifically fertilisers, methanol and petrochemicals)

In each sector, we look at historical production and CO_2 emissions, and show a projection of potential future CO_2 emissions from the sector. These projections are based on announced policies and expected business-as-usual technology gains. In general, except for some specific policies in the power sector, this means we are not assuming significant emission cuts due to (non-CCS) decarbonisation policies. This means that the CO_2 levels shown here are likely upper estimates; these sectors may be decarbonised through CCS, or through a combination of other measures, and the volumes here show the potential for abatement from CCS *and* from other sources rather than from CCS alone.

CO_2 capture from retrofitting power plants will be challenging, but capture from new plants should be designed in

SUMMARY – ELECTRICITY GENERATION

- Thermal generation in the GCC comprises oil and gas fired power plants. The IPP model of many of these facilities poses contractual challenges to retrofitting them with CCUS.
- A number of power plants produce both power and water, for example through multi-stage flash distillation. Developments in reverse osmosis (RO) mean that newbuild CCGTs and RO are usually cheaper than extending their lifetimes.
- We include only grid power supply in this section; captive industrial power plants are included within the relevant industry.
- On a global level, the Petra Nova and Boundary Dam projects are the only power plants that have been retrofitted with CCUS. Both are coal-fired plants and the former suspended temporarily its CCS operations in May 2020.
- 30 new CCUS equipped power plants were announced in the past two years adding up to 30 Mt CO_2 of CCUS capacity. Existing power plants so far appear less likely to retrofit CCUS due to cost and policy concerns.

HEADLINES

Medium capture cost sector – with plenty of projects in planning phase around the world.

Deployment in new plants will be simpler (technically and contractually) than retrofitting existing ones.

Alternatives: Renewables and batteries are seeing large drops in cost and are competitive with fossil generation, although new CCGTs are still expected in all GCC markets. The gradual integration of hydrogen in power generation may also replace gas use in the long term.

Source: IEA

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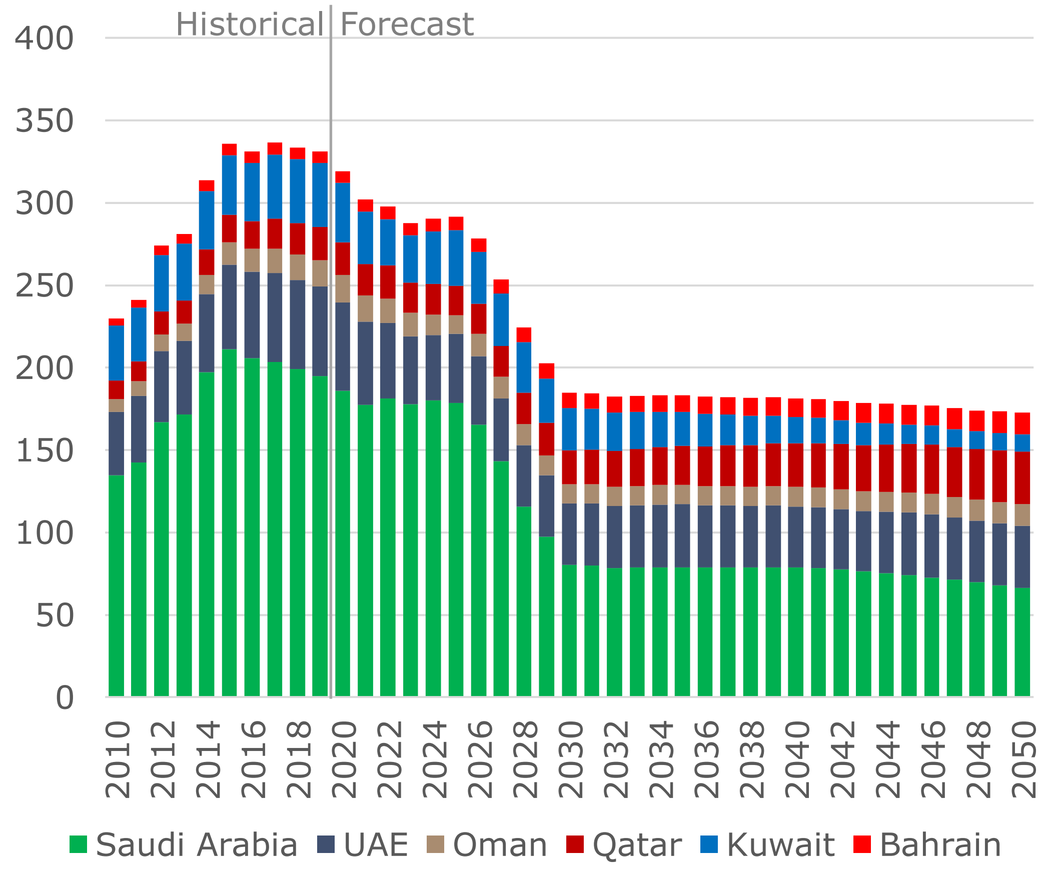
The growth in renewables reduces power sector emissions significantly by 2030, after which there is a steady decline

METHODOLOGY

- Historical electricity generation is obtained from annual reports of electricity utilities and single buyers in the GCC region. These include EWA in Bahrain, MEW in Kuwait, OPWP in Oman, Kahramaa in Qatar, SEC in Saudi Arabia, and EWEC and DEWA in the UAE.
- For future electricity generation, we utilise our in-house modelling tool 'BID3' which ensures that electricity and water needs are met at the minimum system cost.
- We assume power demand grows proportionate to GDP. We also factor in efficiency improvements as economies evolve. This is calculated separately for each GCC nation.
- Water-related power consumption is embedded in our modelling. We expect thermal desalination units to be replaced by reverse osmosis (RO) at the end of plant contracts or plant life.
- The UAE, Saudi Arabia, Bahrain have recently announced their 2050/2060 net-zero plans. In our forecasts, gas contributes similar or lower levels of generation in UAE and Bahrain than the latest announced plans. For Saudi Arabia, we have modified our standard scenarios to include the 50% renewable electricity target in 2030. The country-specific emissions section shows our base scenario for comparison.

FORECAST CO_2 PRODUCTION (Mt)



Sources: IEA

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Several point sources in oil refineries form good opportunities for CO_2 capture, but will not be complete due to distributed nature of these sources

SUMMARY – OIL REFINING

- Major CO_2 emission sources include:
  - process heaters required for the separation of liquid feed and heat for process reactions
  - utilities responsible for the production of electricity and steam
  - fluid catalytic crackers used to upgrade low grade feedstock to more valuable products
  - hydrogen manufacturing, predominantly supplied by SMR units
- Some existing projects capture and store CO_2 from their SMRs like Shell's Quest Refinery and Air Product's SMR at the Port Arthur refinery, Sturgeon Refinery and Preem's Lysekil refinery. Porthos plans to capture CO_2 from several refineries in the Port of Rotterdam
- Hydrogen manufacturing produces high concentration CO_2 streams compared to other refinery emission sources. However, when SMR emissions are combined with the flue gas, the stream is diluted.

HEADLINES

Process CO_2 from SMR is relatively easy to capture due to high CO_2 concentrations, although could also be decarbonised through blue or green hydrogen production.

Complete decarbonisation is challenging due to numerous small emission sources

CO_2 emitter	Description	% of total refinery emissions	Concentration of CO_2 stream
Process Heaters	Heat required for the separation of liquid feed and to provide heat of reaction to refinery processes such as reforming and cracking	30-60 %	8-10%
Utilities	CO_2 from the production of electricity and steam at a refinery.	20-50%	4% (CHP Gas turbine)
Fluid catalytic cracker	Process used to upgrade a low hydrogen feed to more valuable products	20-50%	10-20%
Hydrogen manufacturing	For numerous processes, refineries require hydrogen. Most refineries produce this hydrogen on site. The requirements for Hydrogen increase with demands of stricter fuel quality regulation.	5-20%	20- 99%

Source: IEA

Growth is expected in the oil refining sector until the early 2030’s after which it is expected to plateau but will be tied to the oil price

METHODOLOGY

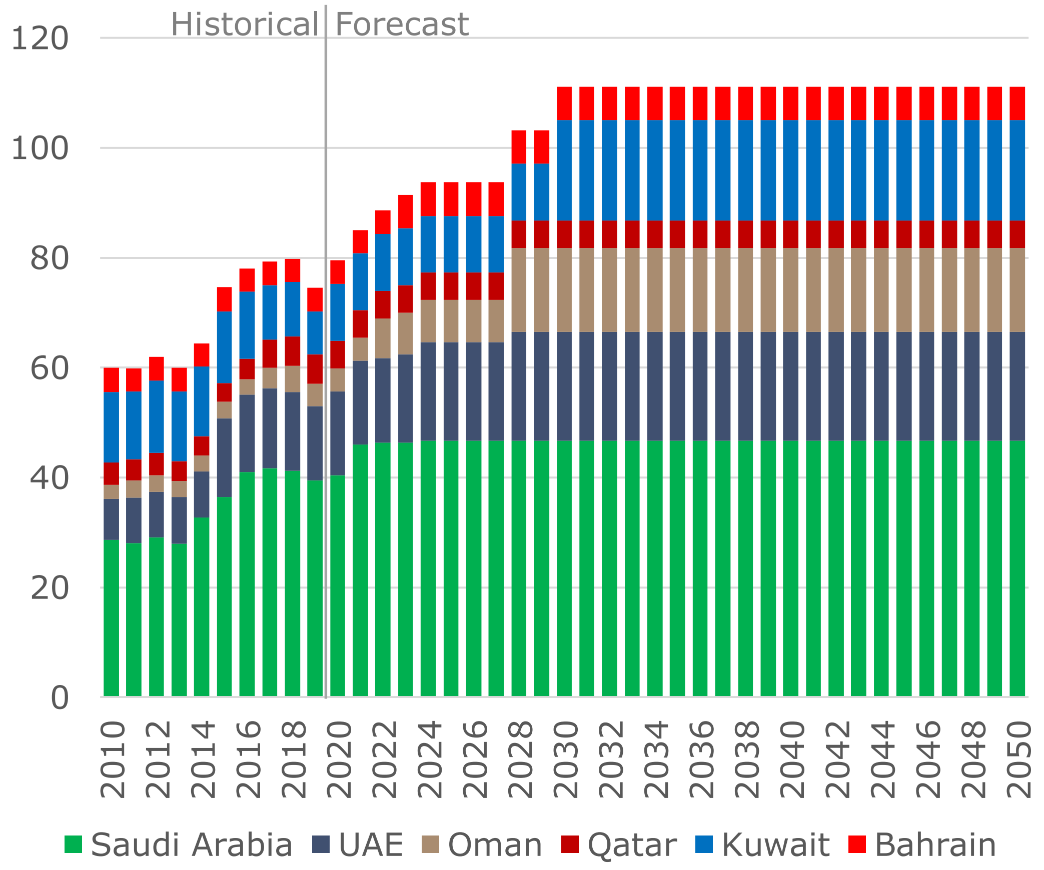
– Refinery capacity growth in each GCC country until 2030 is based on GlobalData’s refinery database. Our forecast assumes that oil refinery output does not grow beyond 2030 and remains flat until 2050 across all countries.

– CO_2 emissions intensities are adapted from Stanford University research which analysed emissions across more than 1500 oil refinery in different geographies including the analysed countries. Emission factors differ for each GCC country.

– Historical refinery production data is adapted from BP Statistical Review of World Energy 2021 report

– Kuwait recently announced a delay in crude oil expansion until the next decade due to low oil prices. Consequently, we assume that GlobalData’s proposed 2021 expansion to 1,400 thousand barrels per day does not happen until 2030.

FORECAST CO_2 PRODUCTION (Mt)



Sources: GlobalData, BP, Stanford University

Natural gas processing offers the easiest and lowest cost of CO_2 capture in the GCC and produces highly concentrated pure streams

SUMMARY – NATURAL GAS PROCESSING & LNG

- CO_2 emissions occur at two different stages in the value chain:
  - Natural gas processing where impurities like CO_2 and sulphur dioxide are separated from natural gas reservoirs to comply with end-user specifications and avoid corrosion. The separation process results in highly-concentrated streams of CO_2 which are easily captured, transported, and stored
  - Liquefaction which requires a lot of energy that fully comes from burning gas, roughly 15% of the amount liquified. Thus, these emissions are associated with process heat and combustion
- Qatargas LNG facilities emit 30 Mtpa of CO_2 at the liquefaction stage and a much lower figure in natural gas processing
- Snøhvit LNG in Norway and Gorgon LNG in Australia have CCS on their natural gas processing facilities only and do not capture CO_2 emissions at the liquefaction stage. Qatargas CCS project sequesters 2.1 Mtpa of CO_2 from Ras Laffan LNG facilities and is expected to expand to 5 Mtpa by 2025

HEADLINES

Capturing CO_2 emissions stemming from the liquefaction of natural gas is quite similar to CCS in the power sector given gas is combusted to power refrigeration compressors and electrical generators. It is considered a medium cost capture process.

High-concentration CO_2 streams resulting from the separation process makes gas processing one of the easiest and lowest cost applications of CCS at the natural gas processing stage

Source: IEA

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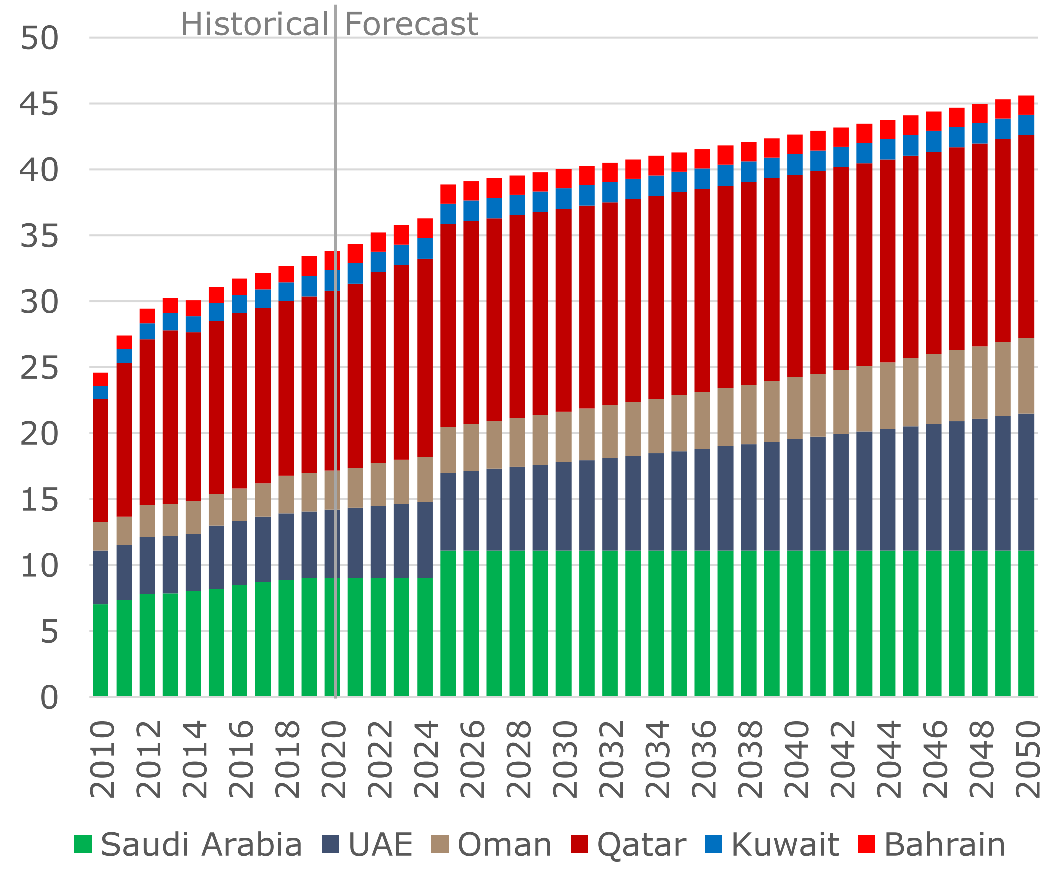
Natural gas processing is expected to maintain steady growth as heavier fuels are phased out and domestic demand for gas in the GCC increases

METHODOLOGY

- We assume that natural gas processing capacity grows with GDP for Oman and the UAE, and only considered announced natural gas capacity expansions in Qatar. We added the planned Jafurah gas processing plant in 2025 in Saudi Arabia. Gas processing capacities in Bahrain* and Kuwait are assumed to be flat until 2050.
- Emission factors of natural gas processing are adapted from a published natural gas processing statistics by the United States Environmental Protection Agency (EPA).
- Historical natural gas processing data is adapted from the U.S Energy Information Administration's (EIA) independent statistics and analysis.
- Natural gas processing capacities are huge in Saudi Arabia due to the massive local demand compared to other GCC countries, while its driven by a mix of LNG exports and domestic demand in Oman, Qatar, and the UAE.
- Saudi Arabia and Bahrain are self-sufficient, and all the produced gas is consumed domestically, whereas Kuwait is a net-importer.

FORECAST CO_2 PRODUCTION (Mt)



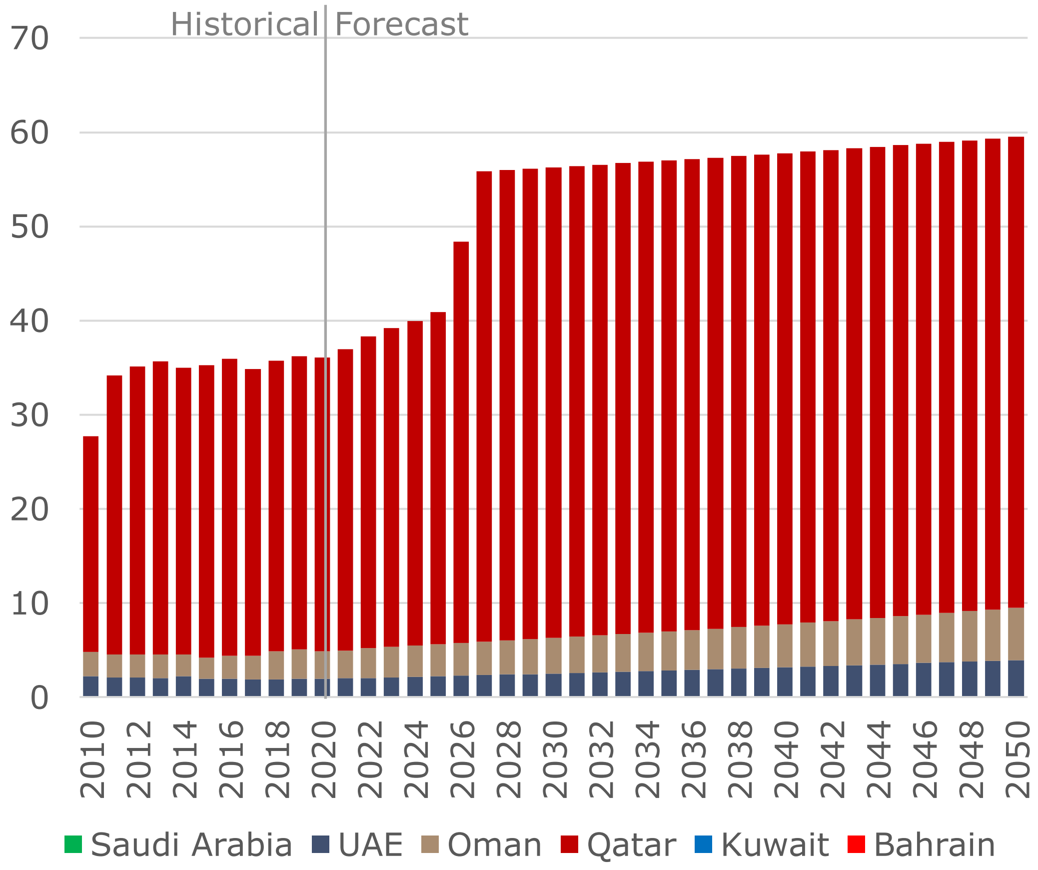
Sources: EPA, EIA, * the unconventional reserves recently discovered (2018) have not been included as no development plan has currently been made public to make a fair assessment and is currently seeking investors to progress to a full FDP

LNG is also expected to grow led by Qatar and supplying global customers as part of their decarbonisation efforts

METHODOLOGY

- We assume that LNG production grows with GDP for Oman and the UAE, and only considered announced LNG terminal expansions in Qatar. The approach differs due to the huge LNG production gap between Qatar and other GCC countries. Qatargas plans to expand production capacity to 150bcm and 170bcm per annum in 2025 and 2027.
- Emission factors of LNG production for Qatar LNG, Rasgas LNG, and Oman LNG are adapted from a published study by the Oxford Energy Institute.
- Historical LNG production data is adapted from BP Statistical Review of World Energy reports.
- Qatar dominates LNG production in the GCC region with eight fully operational LNG facilities producing around 80 million tonnes of LNG per annum. Oman and the UAE are also considered in the forecast despite producing much less than Qatar.
- We assume that Bahrain, Kuwait, and Saudi Arabia do not produce LNG even on the long run.

FORECAST CO_2 PRODUCTION (Mt)



Sources: BP, Oxford Energy Institute

Qatar is also expected to maintain its GTL production

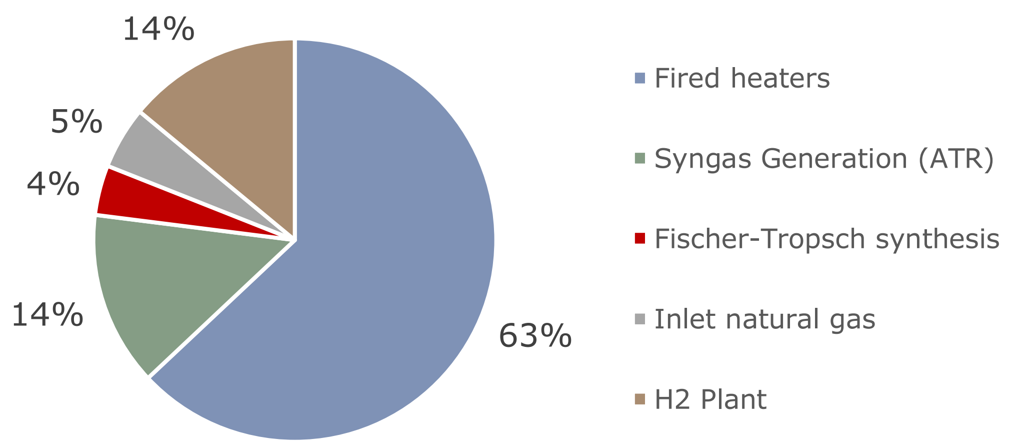
SUMMARY - GTL

- GTL plants have four main CO_2 point sources which are the hydrogen production plant, product workup unit heater, ATR pre-heaters, and steam super heater.
- More than 70% of the Qatar's hydrogen production is for GTL plants. Since hydrogen production results in high concentration CO_2 streams, it could be a potential carbon capture opportunity.
- There are only five GTL plants globally: Pearl and Oryx in Qatar, Bintulu in Malaysia, Escravos in Nigeria, and Mossel Bay in South Africa.
- In 2019, Qatari GTL plants consumed about 5 million tonnes of grey hydrogen

HEADLINES

- Small plant numbers mean CCUS applications in GTL have not been investigated in depth.
  Research papers suggest that post-combustion and oxy-firing carbon capture solutions could be the most feasible and technically effective as the majority of emissions originate in fired heaters

CO_2 sources in a GTL plant



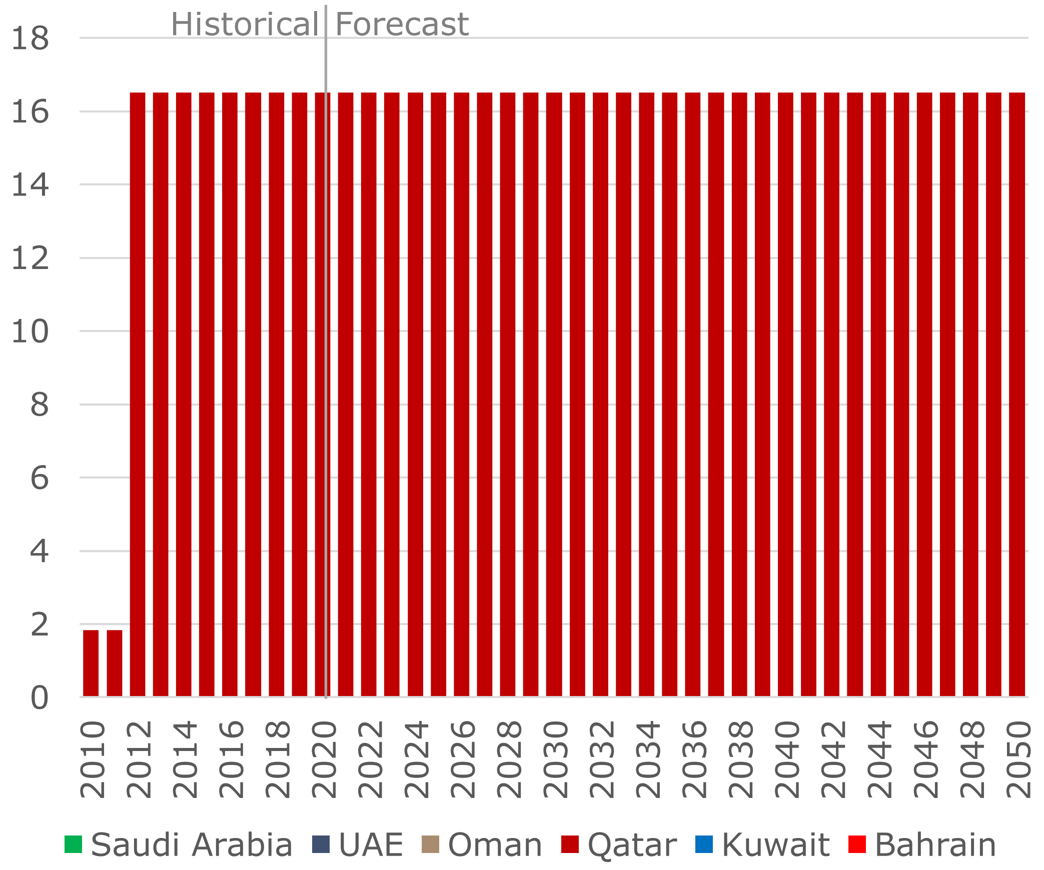
Source: Energy Procedia Journal - Technology Comparison of CO_2 capture for GTL plants

GTL offers multiple opportunities for CO_2 capture including in the hydrogen supply chain

METHODOLOGY

- There are two GTL plants in Qatar that turn natural gas into cleaner-burning fuels and lubricants. These plants are Pearl GTL and Oryx GTL.
- Pearl GTL is the world's largest plant which commenced operation in 2012. The plant is located in Ras Laffan Industrial City and produces more than 200 thousand barrels per day of GTL products
- Oryx GTL has a production capacity of 33 thousand barrels per day of GTL products and it began production in 2007.
- CO_2 emission intensity of GTL is adapted from Oryx's sustainability reports

FORECAST CO_2 PRODUCTION (Mt)



Sources: Shell, Oryx

Significant opportunity exists for CO_2 capture from the power side of aluminium production, but little on the process and has competition

SUMMARY - ALUMINIUM

- Captive power generation is the primary source of CO_2 emissions in aluminium smelting, responsible for about 60% of emissions where a smelter uses captive CCGTs. The remaining 40% are process emissions, largely from the use of carbon in the reduction process.
- In the GCC, aluminium power typically comes from captive natural gas power plants. For example, Aluminium Bahrain (ALBA) operates three power stations with a cumulative capacity of 3.7GW. We have included these emissions as associated with ‘aluminium’, not as ‘power’.
- Low CO_2 concentrations in process emissions (around 1% by volume) make CCUS challenging to apply. In addition, the presence of oxygen in the flue gas stream requires the use of modified solvents to absorb CO_2.
- Although captured CO_2 from the smelting process is challenging, carbon capture equipment could potentially be retrofitted to enable the continued operation of existing captive power plants in aluminium smelters

HEADLINES

Significant capacity for CCUS on captive power generation at medium cost.

CCUS faces competition with alternative methods to decarbonise firm power, such as captive renewables and batteries or sourcing more grid electricity.

CCUS on process emissions is still at the concept stage because of the very low concentration of CO_2 in exhaust gases. Research into options for replacing carbon anodes represents an alternative potential route to decarbonise process emissions.

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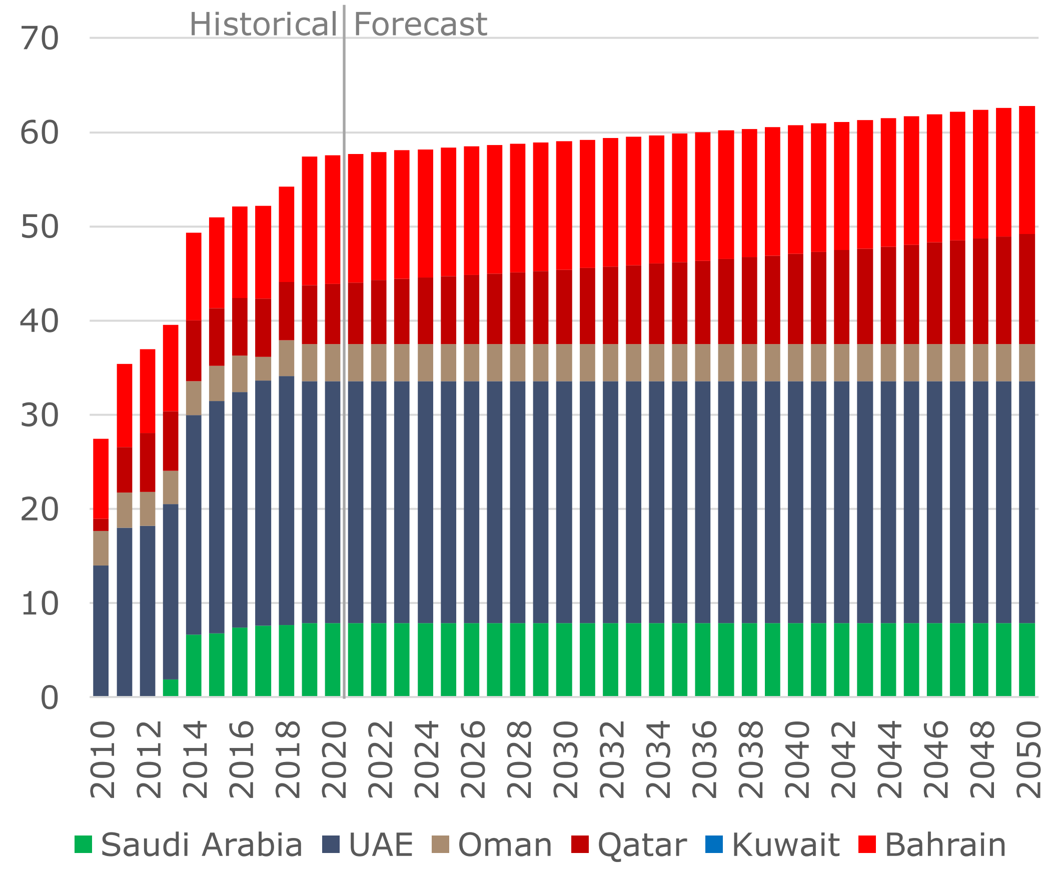
Aluminium production is expected to increase driven by low cost and extensive renewable generation

METHODOLOGY

- We assume that aluminium production remains flat on the long-run in all GCC countries except Qatar. The most recent aluminium plant expansion in the GCC region happened in 2019 when ALBA introduced a sixth production line. As for Qatar, we assume that low natural gas prices will drive aluminium production which currently stands at 0.6 Mtpa only. We assume that Qatari aluminium production grows proportionate to the GDP.
- Aluminium production is electricity-intensive and hence emission factors from the combustion of natural gas are adapted from the IEA report on CO_2 emissions from fuel combustion. We assume that electricity intensity of aluminium production remains flat over the forecast period. The intensity is based on actual electricity consumption and aluminium production figures in the GCC as reported by the International Aluminium Institute (IAI).
- Historical aluminium production data is adapted from the United States Geological Survey (USGS) Statistics between 2000 and 2019.
- The aluminium industry is electricity intensive and the bulk of emissions come from on-site captive power plants as is the case in ALBA and EGA. Both of these facilities utilise CCGTs to power their aluminium production. Electricity emissions account for 60% of total aluminium production emissions.

FORECAST CO_2 PRODUCTION (Mt)



Sources: International Aluminium Association, IEA, CM Group

CO_2 capture from steel is possible but faces competition from alternative processes with a greater impact on decarbonisation

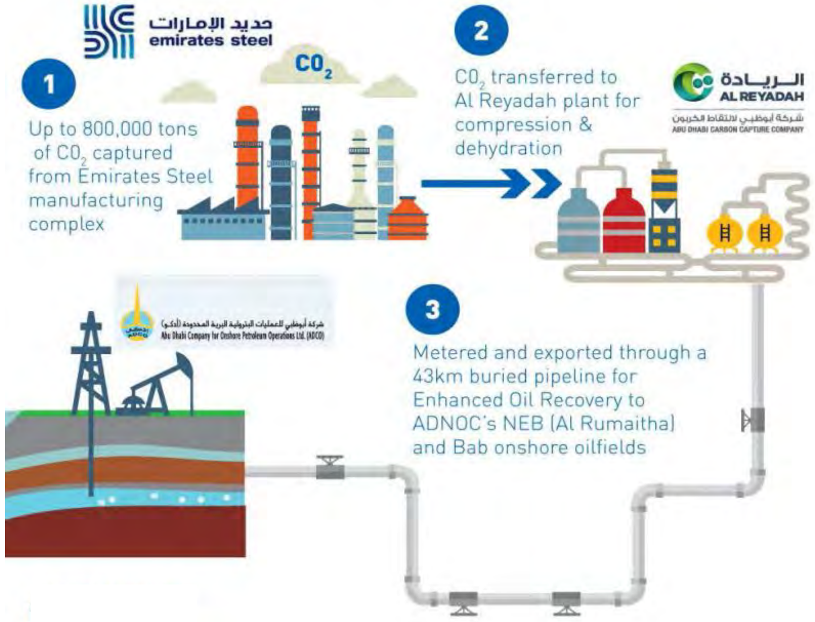
SUMMARY – IRON & STEEL

- GCC steel facilities are all gas-based direct reduction plants that utilise either the Midrex or the Energiron technology
- The majority of CO_2 emissions occur when iron ore is reduced during iron production which takes place in the shaft furnace. Emissions occur to a much lesser extent during the production of steel as the carbon in the iron is oxidised to CO_2. Both of these processes are performed at integrated steel facilities as is the case in the GCC region
- Al Reyadah (Abu Dhabi Carbon Capture Company) launched the world's first commercial retrofit CCS in the iron and steel industry in Abu Dhabi. The project captures 0.8 Mtpa of CO_2 from Emirates Steel using an absorption and recovery system. The CO_2 is utilised by ADNOC for EOR

HEADLINES

Some cheap capture streams but capture from all CO_2 streams is challenging

CCUS appears competitive for decarbonisation but faces competition from alternative steel making processes, such as hydrogen-based production



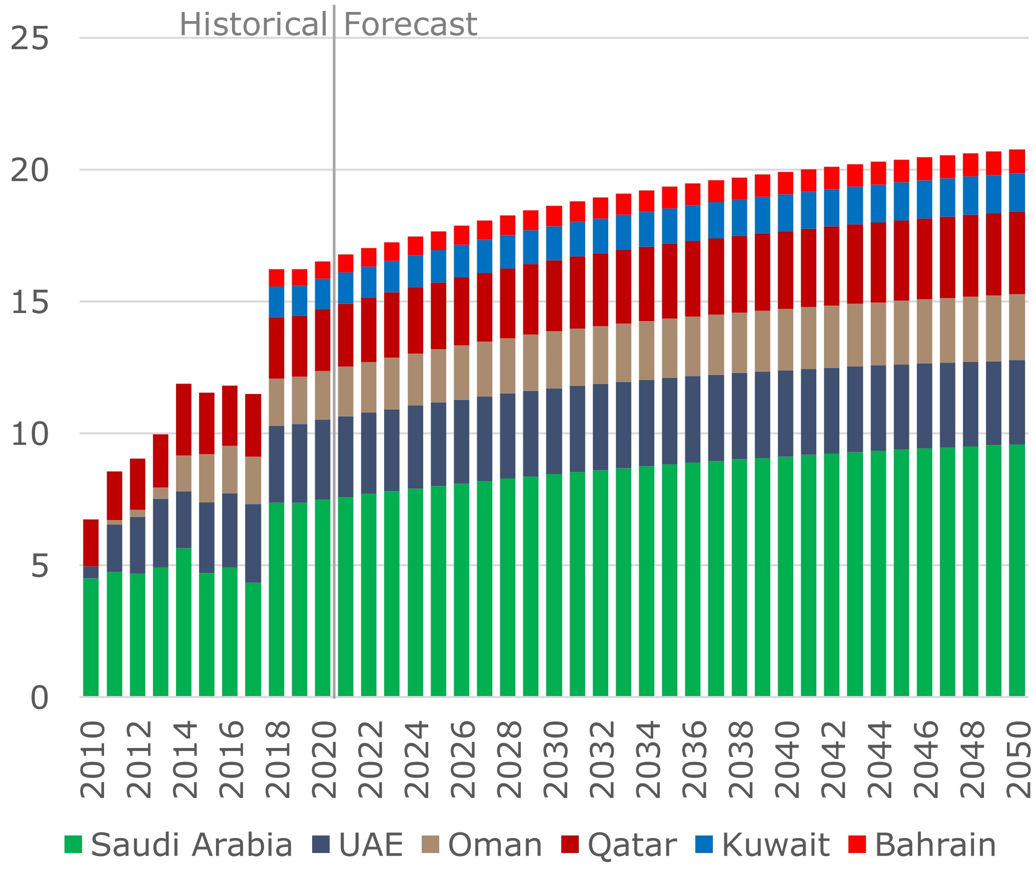
Source: IEA

Since the forecast for steel production is growth a choice between green steel and low carbon steel will have to be made

METHODOLOGY

- We assume that iron and steel production grows proportionate to population growth because just like cement, steel is heavily used in construction in the GCC.
- We assume that the industry will rely on natural gas for the direct reduction of iron ore which is crucial step in steel production. The CO_2 emission factor used is based on natural gas-based steel production from the IEA analysis which assumes a natural gas consumption of 10.1 GJ/t Steel.
- Historical steel production data is adapted from the World Steel Yearbook Statistics between 2000 and 2019.
- Based on historical data, the surge in steel production in 2018 is attributed to doubling production in Saudi Arabia which reached 8.1 million tonnes in 2019, and the inauguration of commercial scale steel facilities in Kuwait and Bahrain in the same year.

FORECAST CO_2 PRODUCTION (Mt)



Sources: IEA, World Steel

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CO_2 capture from cement is currently high cost but there are some promising technologies that could bring the cost down

SUMMARY - CEMENT

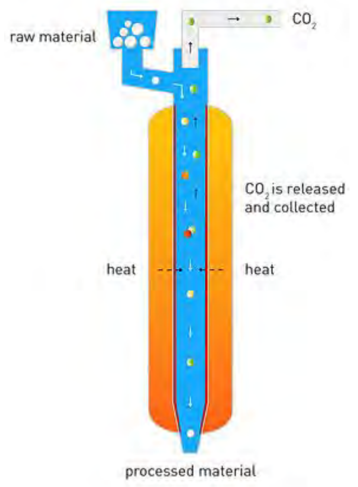
- The majority of emissions from cement production are associated with the heating of raw materials including limestone to temperatures above 1000ºC to produce clinker. Approximately two-thirds of cement emissions are "process emissions" from this calcination process, while the remaining emissions come from the energy used for heating this and other processes.
- In the GCC the energy-related emissions mostly come from natural gas, except in Saudi Arabia where many cement plants are oil-based.
- Cement is generally considered a "hard" sector to capture CO_2 from, with high cost estimates from e.g. GCCSI
- There are breakthrough technologies being developed with the promise of reducing capture costs. One example is the LEILAC demonstrator plant in Belgium, that seeks to produce a pure CO_2 stream from the calcination emissions via a process re-design (image to the right) that sees limestone broken down in a sealed vessel with no exposure to outside air.

HEADLINES

High capture cost sector

Significant potential for breakthrough technologies to drastically lower capture costs, e.g. LEILAC

Few alternatives: high temperature heat could come from hydrogen; process emissions difficult to avoid.



Source: Leilac image from https://www.project-leilac.eu/the-core-technology

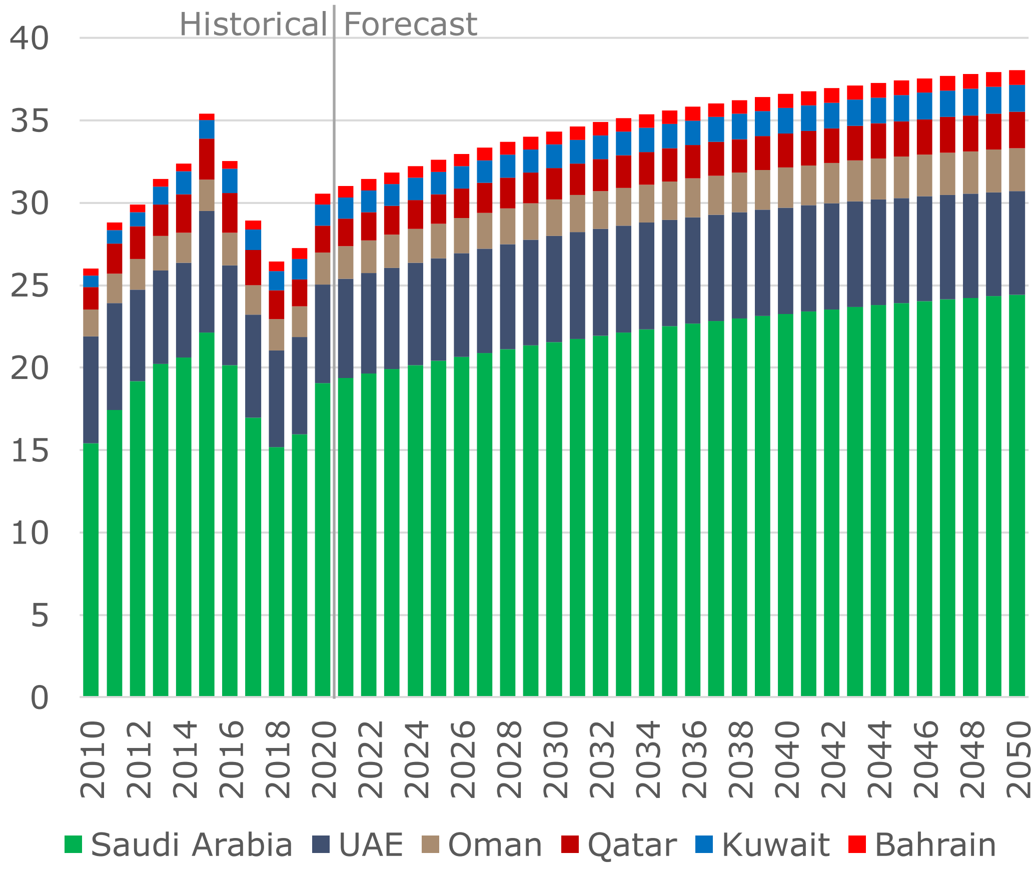
Gaffney Cline AFRY ÅF PÖYRY

With the expected growth in the cement sector there will need to be a solution to decarbonise the industrial heat and the process

METHODOLOGY

- We assume that cement production grows proportionate to population, calculated separately for each GCC nation.
- We assume that the energy use associated with clinker production drops from 3.3GJ/t in 2020 to 3.1GJ/t by 2030 (in line with the IEA SDS global average) and 2.9GJ/t by 2050, and that the clinker fractions fall from 70% (2020) to 67% (2030) and 65% (2050). This leads to an emissions intensity reduction of 6.1% in 2030, and 10.7% in 2050, compared to the assumed 2020 intensity of 0.507tCO_2/t Cement when energy is sourced from natural gas.
- We assume that cement production uses a 50/50 split of oil and natural gas, before shifting completely to natural gas in 2030. The emissions intensity of oil-based cement production is used as 0.56 tCO_2/t Cement.
- Historical cement production data is adapted from the United States Geological Survey (USGS) Statistics between 2000 and 2019.
- 2020 data for Saudi Arabia is based on recent announcements by the Saudi Central Bank which indicate a significant increase in cement production in 2020, while other 2020 figures are forecasts.
- Just over two-thirds of CO_2 emissions from making cement with natural gas come from the chemical reactions that take place when clinker is created through calcination of limestone rather than from the provision of heat.

FORECAST CO_2 PRODUCTION (Mt)



Sources: GlobalData, IEA, United Nations Population Division

Fertilisers and methanol have great potential for CO_2 capture but are likely to be replaced with green alternatives in the long term

SUMMARY - FERTILISERS

- Ammonia is synthesised by the Haber-Bosch process which combines hydrogen from the steam reformation of natural gas with nitrogen from air. Steam reforming is energy-intensive and hence emits large quantities of CO_2. About 27% of pure hydrogen produced globally is used for ammonia production, with emissions from hydrogen production accounting for more than of those from the entire ammonia production process
- The CO_2 generated in ammonia production could be captured and stored, or used on-site to manufacture urea
- Similarly, the production of methanol also involves the steam-methane reforming process which results in CO_2 emissions
- A number of ammonia and methanol plants already capture CO_2, either for storage or commercial sale
- According to the IEA, the cost of CCUS-equipped ammonia and methanol production is typically around 20-40% higher than that of their unabated counterparts

HEADLINES

CO_2 capture is cheap due to high purity CO_2 streams.

On-site CCUS may face competition from blue and green hydrogen sources

$$CH_4 + H_2O \leftrightarrow CO + 3H_2$$
$$CO + H_2O \leftrightarrow CO_2 + H_2$$
$$CH_4 + 2H_2O \leftrightarrow CO_2 + 4H_2$$

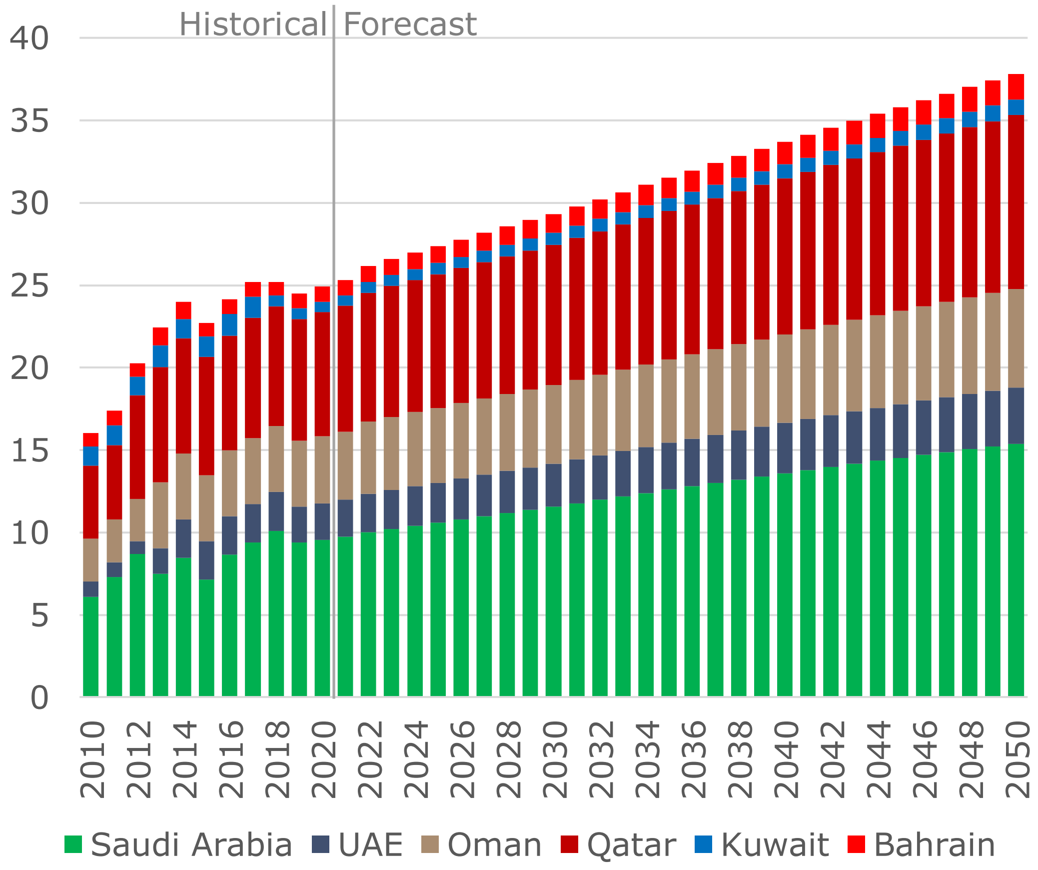
Source: IEA

Global demand for fertiliser is expected to grow and GCC production of green and blue ammonia and methanol would give a competitive edge

METHODOLOGY

- We assume that fertilisers production grows proportionate to GDP as the GCC region is a net exporter of fertilisers.
- Emission factors are adapted from the IEA's 'Future of Hydrogen' report. The emissions factor starts as 2.35kgCO_2/kgNH_3 and decreases to 2.14kgCO_2/kgNH_3 by 2030 and 1.8kgCO_2/kgNH_3 in 2050.
- Historical fertilisers production data is adapted from USGS Statistics.
- Saudi Arabia is the dominant fertilisers producer with Ma'aden and SAFCO producing 6.5 Mtpa.
- Qatar and Oman follow with Qatar Fertiliser Company contributing to 8 Mtpa, and Oman India Fertiliser Company and Sohar International Chemical Industries adding 2.5 Mtpa.

FORECAST CO_2 PRODUCTION (Mt)



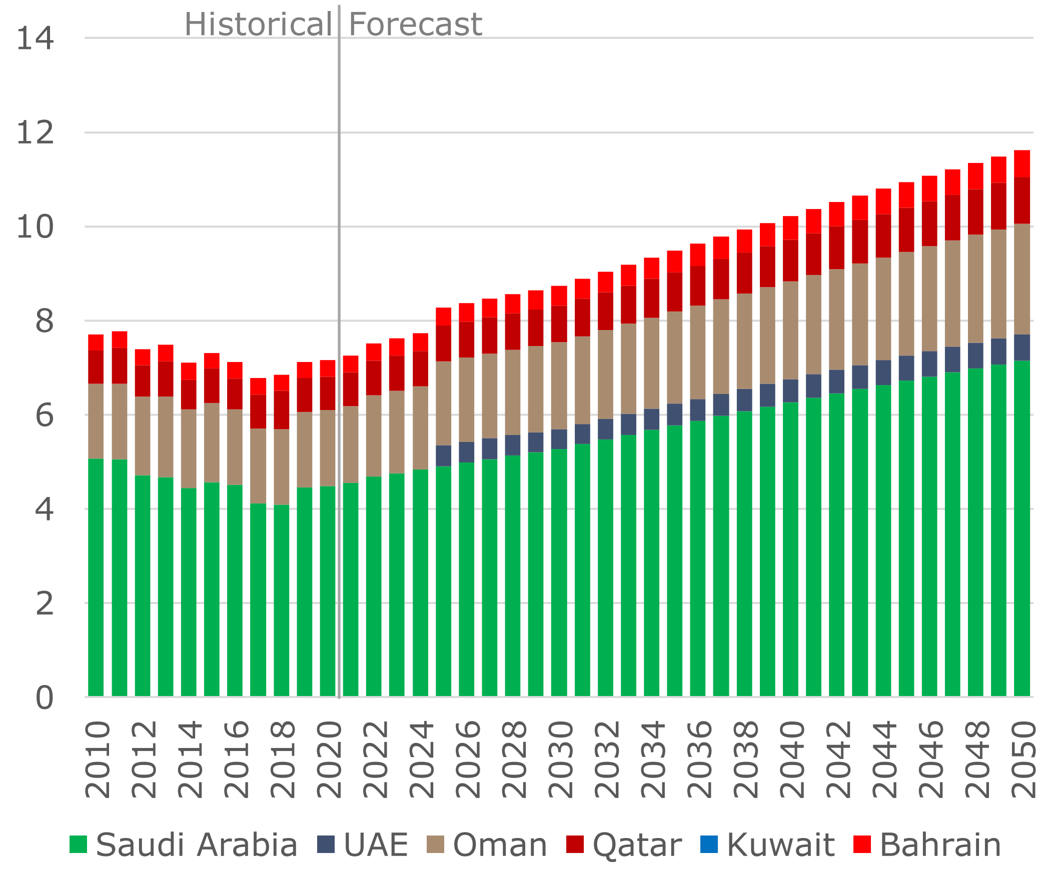
Sources: GPCA, IEA

Alongside ammonia, methanol as a carrier of hydrogen or feedstock will likely be valued if produced as either green or blue

METHODOLOGY

- We assume that methanol production grows proportionate to GDP.
- We assume that the emission factor decrease slightly in 2030 and in 2050 based on the IEA views on methanol emission intensity. The emissions factor starts at $0.8kgCO_2/kgMeOH$ and drops to $0.7kgCO_2/kgMeOH$ in 2030 and to $0.6kgCO_2/kgMeOH$ in 2060.
- Historical methanol production data for Bahrain and Oman is adapted from USGS until 2018. For both countries, 2019 data is assumed to be the same as 2018. For Saudi Arabia and Qatar, the data is adapted from GlobalData statistics.
- There is no commercial scale methanol production in Kuwait and the UAE. We assume that Kuwait does not produce methanol even on the long run whereas the UAE starts producing at a commercial level in 2025 with the inauguration of the 0.4 Mtpa Ruwais Methanol plant.

FORECAST CO_2 PRODUCTION (Mt)



Sources: GPCA, USGS, GlobalData

CO_2 capture from petrochemicals is a relatively cheap option with few alternatives for decarbonisation

SUMMARY - PETROCHEMICALS

- A significant quantity of CO_2 emissions in the petrochemicals industry originates from syngas derived from fossil fuels. Remaining CO_2 emissions are from process side reactions during the production of petrochemicals.
- Process emissions generally occur at high purity and pressure, and hence are relatively easy to capture. In Ethylene processes, nearly all process emissions are from the combustion of process off-gas
- Energy emissions are challenging and relatively expensive to capture as CO_2 is produced as a dilute low pressure stream.
- Future syngas production may be from ATRs, which would simplify the capture process.

HEADLINES

Cheap sector to capture process emissions, and few alternative options

Retrofitting capture on energy emissions is more challenging. Capture may become easier if ATRs are used, or emissions may be reduced through electrification with renewables.

Source: IEA, EPA

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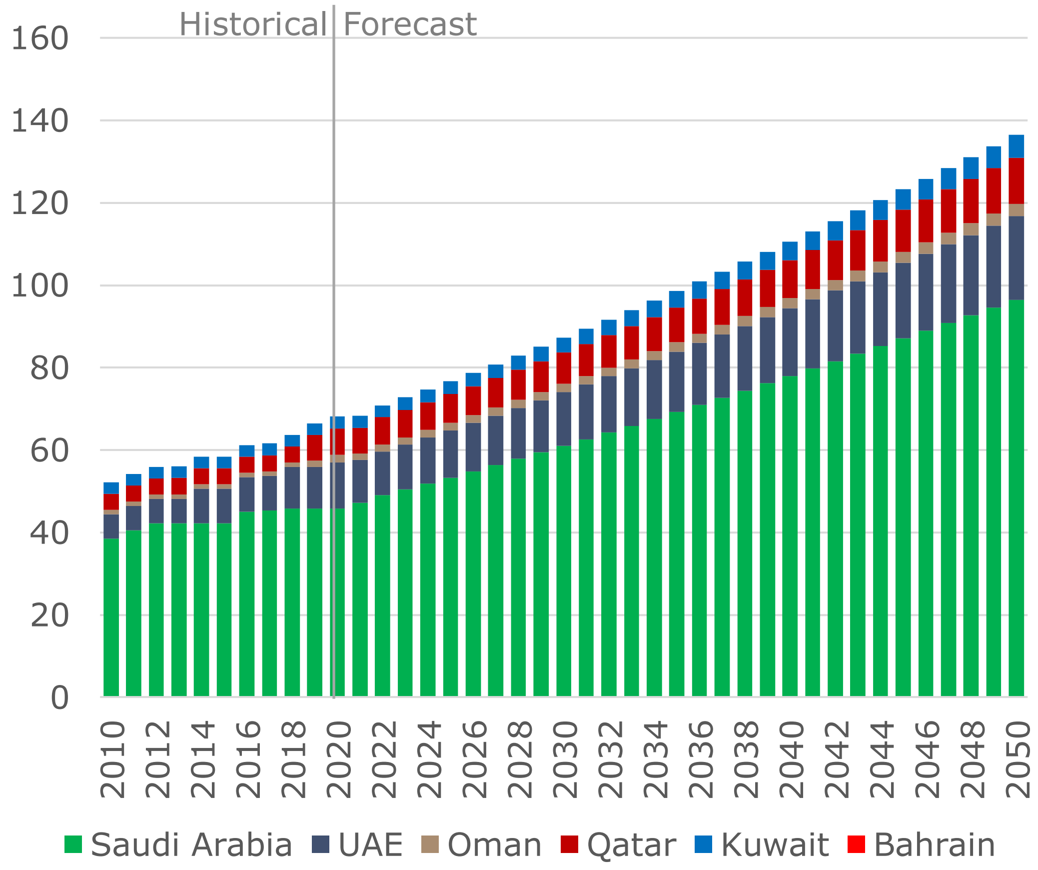
Significant growth in petrochemicals is expected in Saudi Arabia and UAE making it a key sector to decarbonise

METHODOLOGY

- The analysis of petrochemicals includes ethylene and propylene.
- We assume that petrochemicals production grows proportionate to GDP.
- Historical ethylene and propylene data is adapted from GlobalData including 2020
- Ethylene emissions factor is adapted from EcoCatalytic estimation of conventional cracking which is assumed to be 1.5 tCO_2/t Ethylene for the entire forecast period. Propylene carbon intensity is assumed to be 3.4 tCO_2/t Propylene for the entire forecast period.
- Saudi Arabia produces most of the ethylene and propylene in the GCC region while Bahrain does not contribute to the petrochemicals market at commercial scale

FORECAST CO_2 PRODUCTION (Mt)



Sources: GlobalData, IEA, United Nations Population Division

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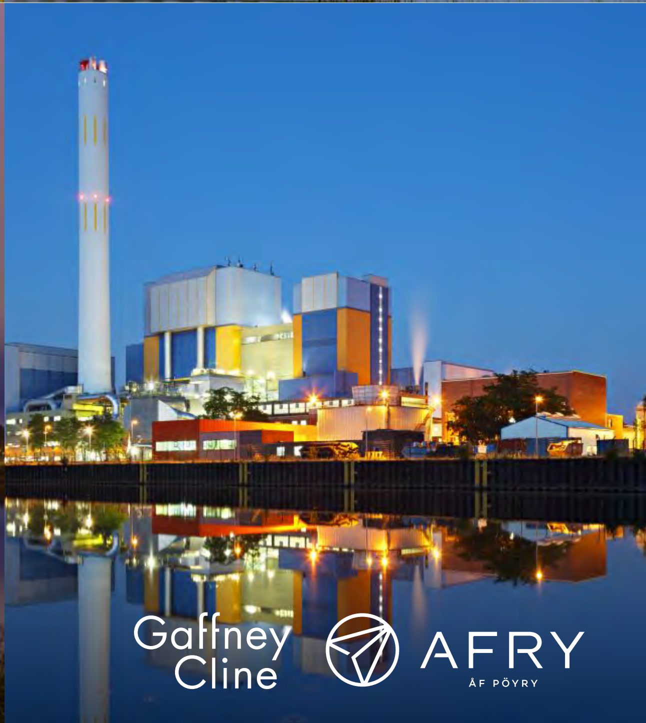
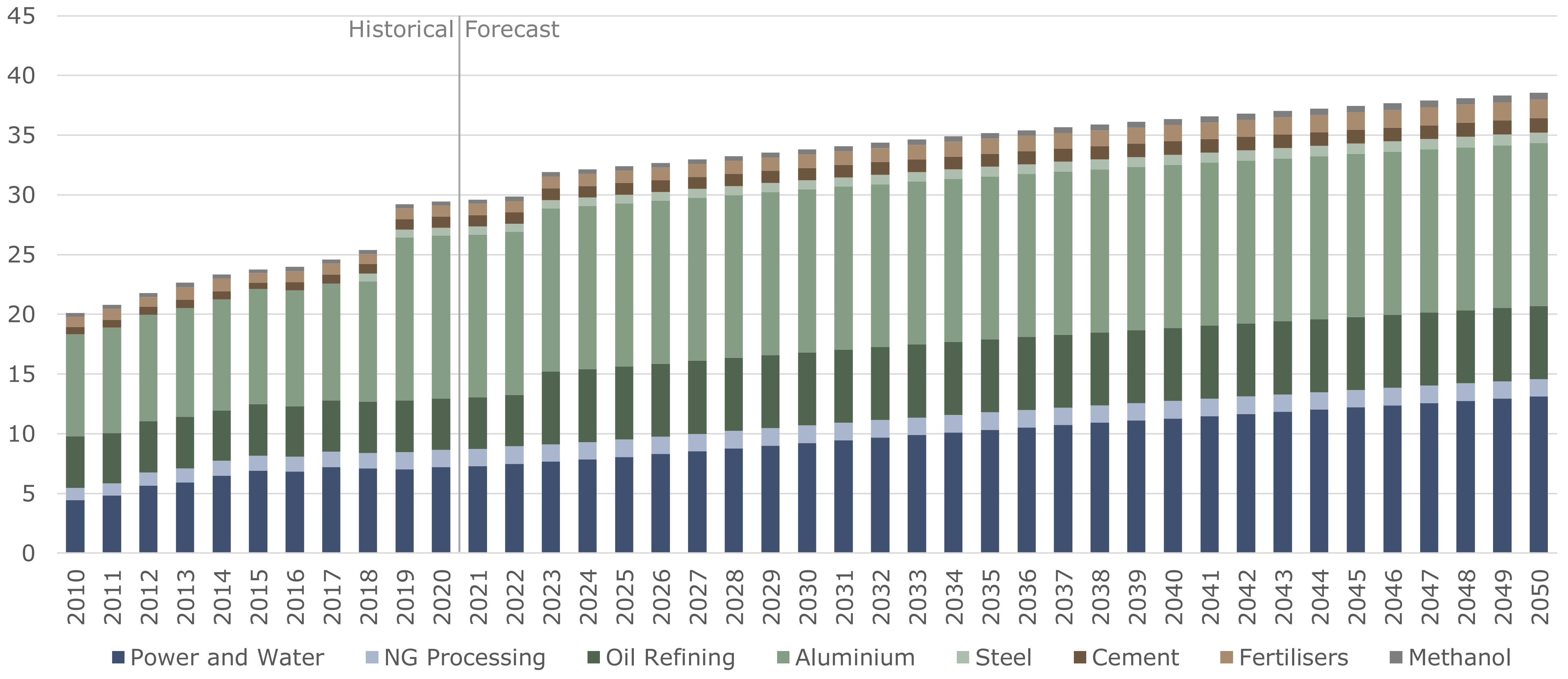
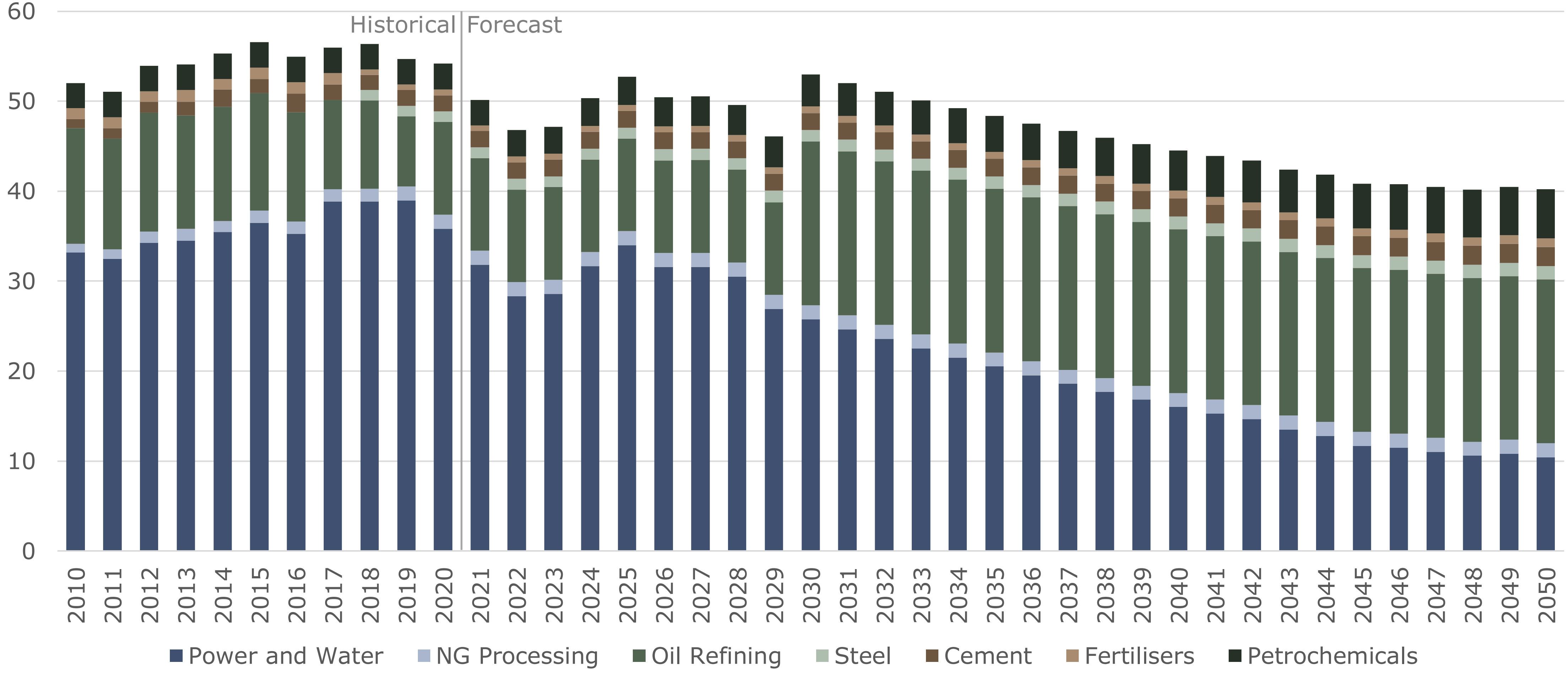


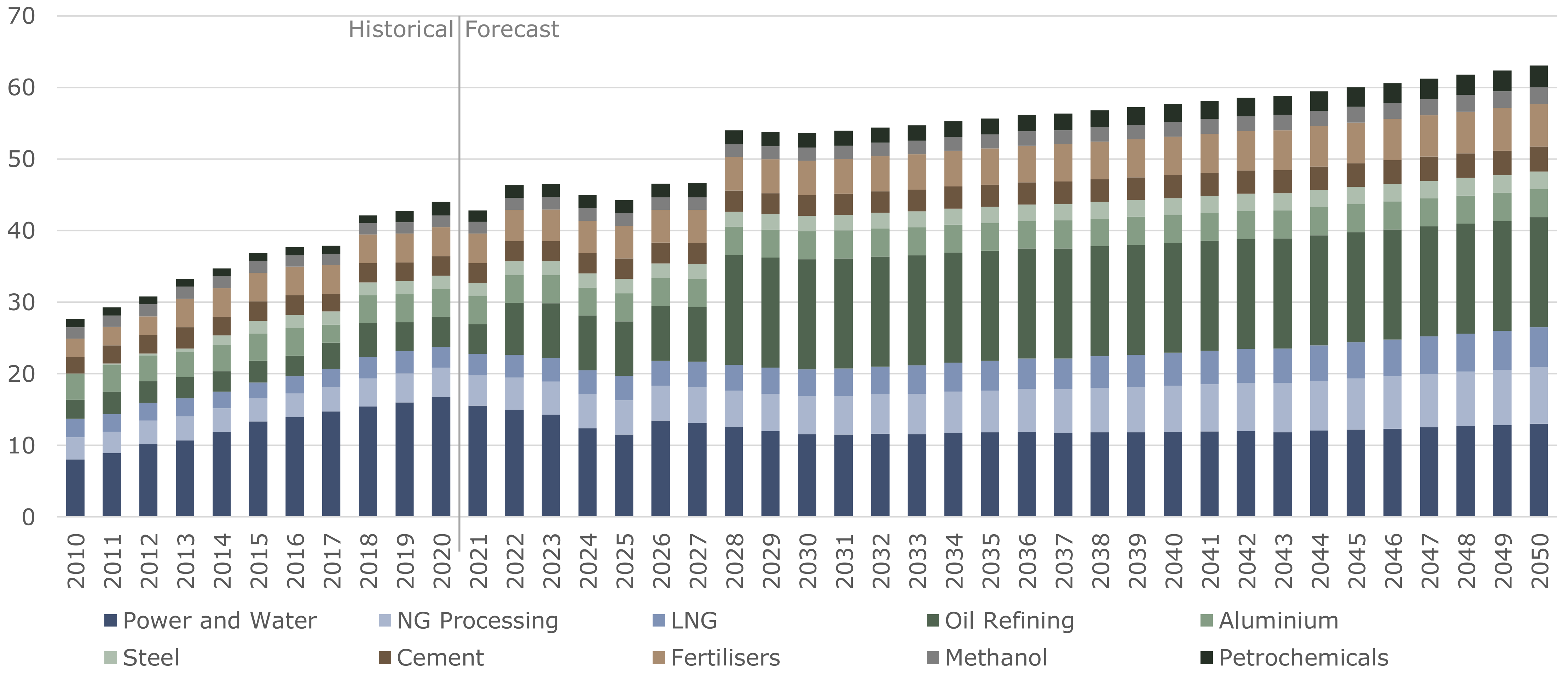
Total forecast industrial emissions (Mt, 2010-2050) - Bahrain



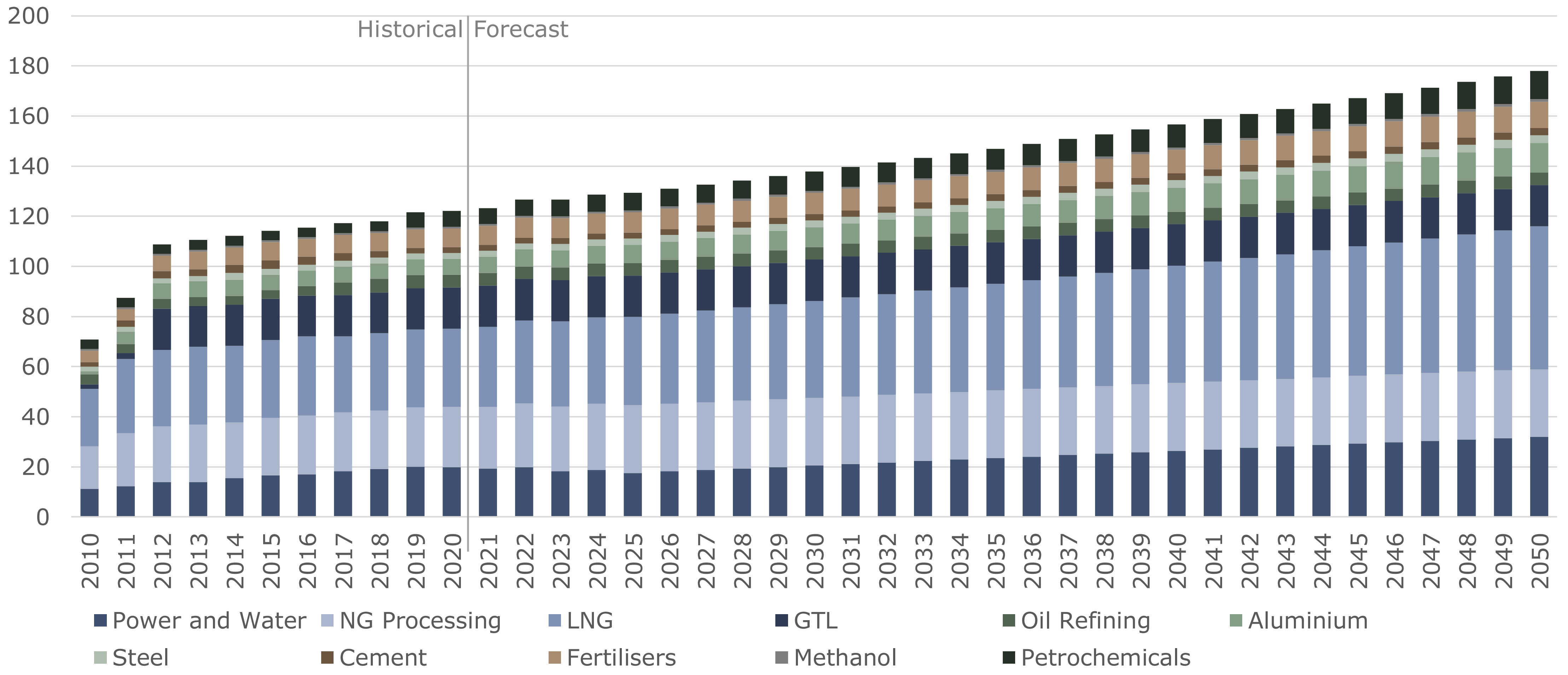
Total forecast industrial emissions (Mt, 2010-2050) – Kuwait



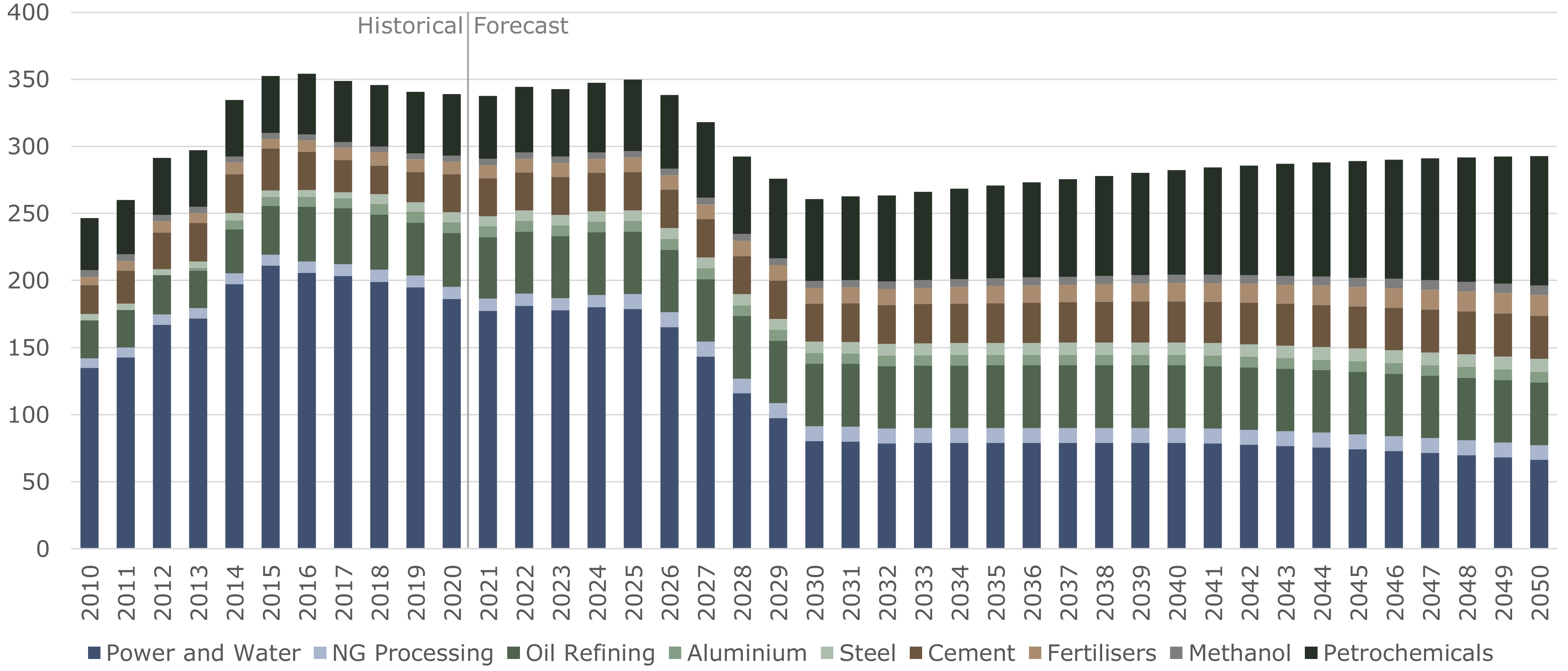
Total forecast industrial emissions (Mt, 2010-2050) - Oman



Total forecast industrial emissions (Mt, 2010-2050) - Qatar



Total forecast industrial emissions (Mt, 2010-2050) - Saudi Arabia



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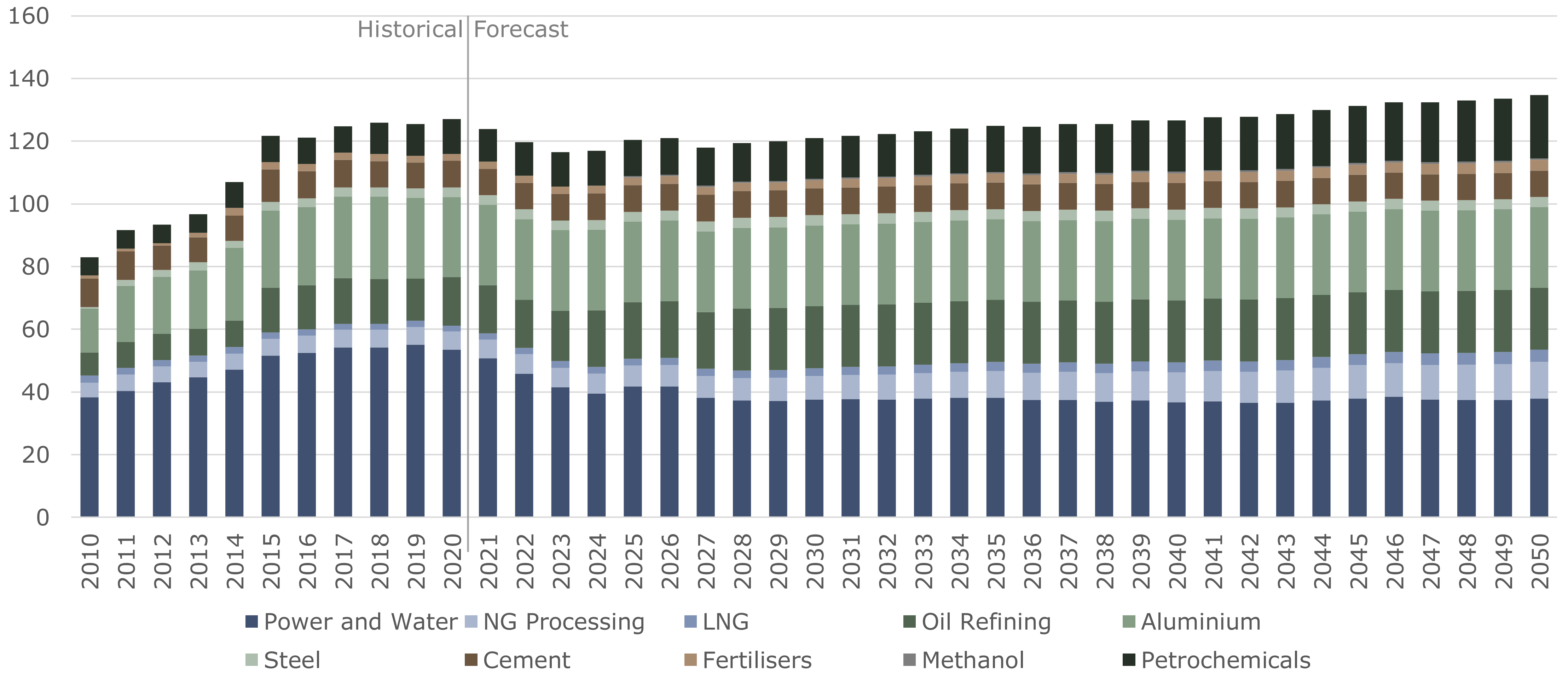
Total forecast industrial emissions (Mt, 2010-2050) - United Arab Emirates



CHAPTER 3

Carbon Sinks

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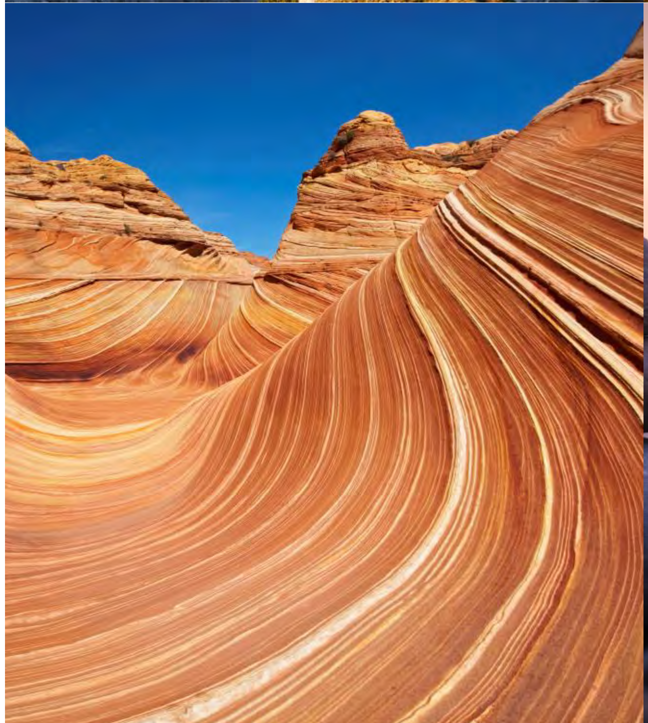

The GCC has the potential to be a world class hub for CCUS based on known geological conditions but the opportunity has yet to be fully quantified

Knowledge of the subsurface is invariably good for depleting and depleted gas reservoirs, from seismic, drilling and dynamic data acquired during the exploration, appraisal and development life cycle, in comparison to other potential storage sites such as saline aquifers. Uncertainties with respect to the three fundamental considerations of any CCS project in subsurface formations, namely capacity, injectivity and containment, are usually well understood for depleted gas reservoirs (due to data obtained and analysis performed during appraisal and production), providing a sound basis for ranking and selecting sites and for evaluating risk mitigation strategies.

In this work GaffneyCline has focused on the estimation of capacity and has addressed injectivity and containment in general terms as they relate to individual formations.

Capacity – How much CO_2 can be stored?

A simple but reliable approach to estimate capacity for CO_2 storage in depleted gas reservoirs is through material balance, using the link between the volume of hydrocarbon gas that has been produced and the volume of CO_2 that could be injected to replace the produced volumes (illustrated on next slide). The approach and detail of analysis is determined by the availability of data. Material balance is the basis for the calculations undertaken by GaffneyCline in this work.

Injectivity - How fast can CO_2 be injected?

Well productivity in depleted gas reservoirs is well known due to historical production and therefore reliable estimates of the reverse process, i.e. injectivity can usually be made. Injectivity can be adversely affected by various factors, including for example aquifer influx that may have occurred during production, certain hysteresis effects and the maximum safe bottomhole injection pressure that can be tolerated during injection operations. (Note that, in most cases the wells will have to be recompleted for injection).

Containment - How safely can CO_2 be stored for a long time?

Gas reservoirs, by their nature, have demonstrated containment integrity by trapping hydrocarbon gas over geologic time. Therefore, the risk of leakage is generally low, provided that the structure is not filled beyond spill. The most important factor that affects risk for containment in depleted gas reservoirs is integrity of the existing wells. Poor and deteriorating cement bonds around casing can lead to leakage behind pipe to shallower formations or even to surface. However, remedial actions are often possible. Other factors that may affect containment include, for example, channeling of injected gas through high permeability zones beyond structure and reactivation of faults during depressurization. (Note that if the wells have previously been stimulated / fracked this may affect containment).

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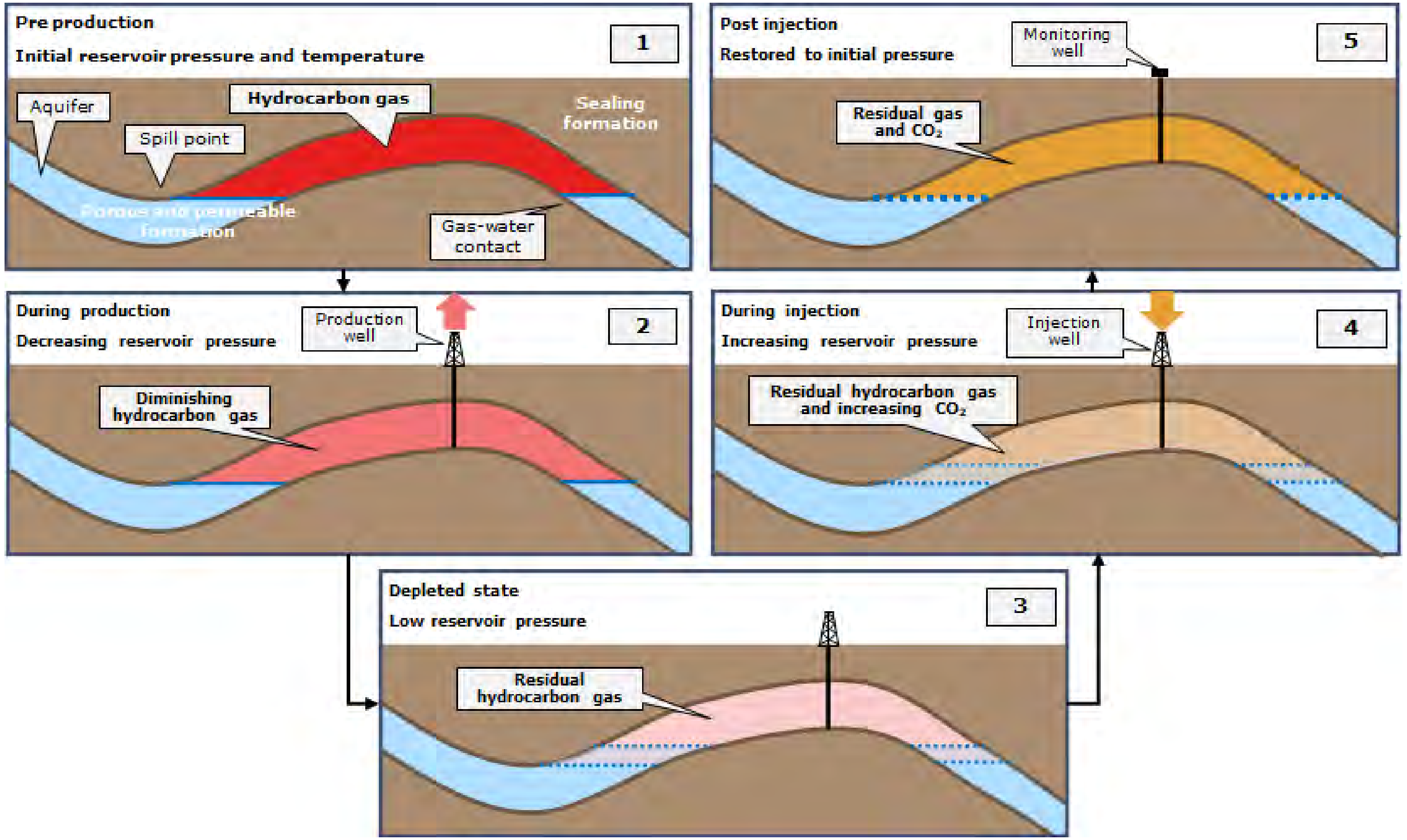
Significant potential exists in both depleted reservoirs and saline aquifers close to emissions hubs



DESCRIPTION

- Illustration of simplest form of CO_2 storage in depleted gas reservoirs.
- CO_2 is injected into a depleted gas reservoir to restore pressure to its original pre-development value.
- Uncertainties in estimating storable quantities relate, inter alia, to aquifer influx, hysteresis effects, maximum permitted bottomhole injection pressure, channelling of CO_2, unequal fill due to heterogeneities, etc.

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A top down up approach was taken to analyse the carbon sinks across the GCC

GaffneyCline has reviewed available data for the gas fields in the Middle East and has concluded that public information of individual fields is too sparse to allow a meaningful bottom-up approach to be followed. Furthermore, a bottom-up approach would, at best, only provide information about a limited number of specific fields and would provide a distorted view of the overall potential for CCS in depleted gas reservoirs in the region.

GaffneyCline therefore sought information that would allow a top-down approach to be followed. The single most important item of information needed to estimate CCS potential of a depleted gas reservoir is the volume of hydrocarbon gas that will be recovered over field life (ultimate recovery). Several sources of data have been drawn on to obtains estimates of past and future production of non-associated gas at country level.

GaffneyCline has assimilated information on past and future projections of oil and gas at country level from the following sources:

- BP
- Energy Information Administration (EIA)
- OPEC
- Oher public domain sources

Reported volumes of gas (historical and future projections) from some sources include both associated and non-associated gas (i.e. gas that has been produced as a byproduct of oil and gas that has been produced from gas reservoirs). For gas storage purposes, only the non-associated gas is relevant. GaffneyCline has made certain assumptions about solution gas-oil ratios to estimate the volumes attributable to non-associated gas reservoirs only.

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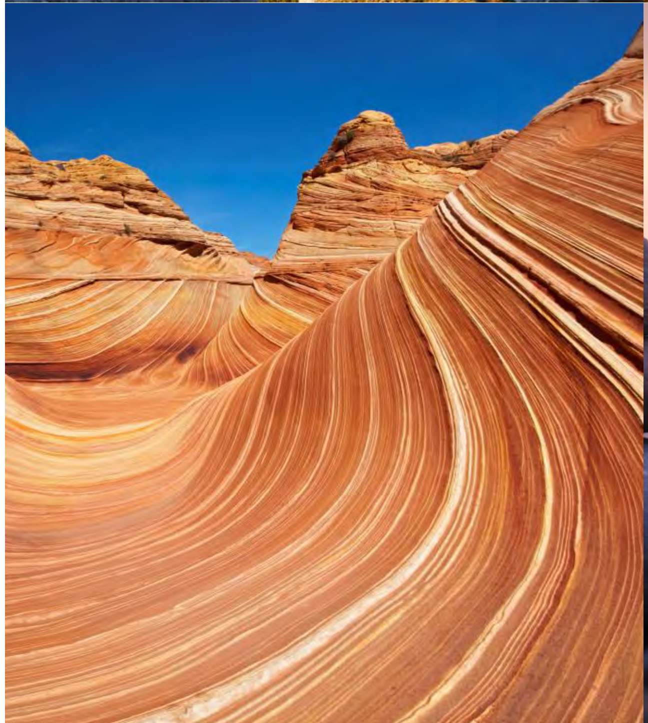
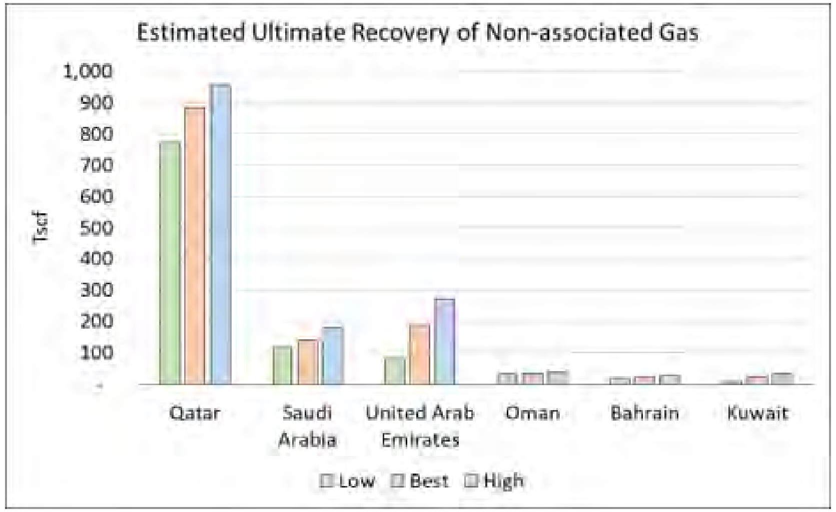


Using public data the volumes of non-associated gas were calculated to assess the potential volume in depleted gas reservoirs

ULTIMATE RECOVERY OF NON-ASSOCIATED GAS

- Gaffney Cline has compared the information from different sources to make estimates of uncertainty ranges (Low case, Best estimate case and High case) of ultimate recovery of non-associated gas per country. These are shown in the diagram and table.
- Reported volumes of gas (historical and future projections) from some sources include both associated and non-associated gas.
- For gas storage, only the non-associated gas is relevant. GaffneyCline made certain assumptions about solution GOR's to estimate the volumes attributable to non-associated gas reservoirs only.
- Estimates of ultimate recovery of non-associated gas at country level were converted to theoretical estimates of storable volumes. In practice, these quantities are unlikely to be reached for the following reasons:
  - Not all depleted reservoirs are suitable for CCS (suitability factor).
  - Not all suitable reservoirs can be filled to the theoretical maximum (efficiency factor).

Country	EUR of Non-associated Gas (Tcf)		
	Low	Best	High
Qatar	772	886	956
Saudi Arabia	114	138	178
United Arab Emirates	79	188	274
Oman	31	33	39
Bahrain	16	21	26
Kuwait	7	24	34
Total	**1,020**	**1,291**	**1,507**



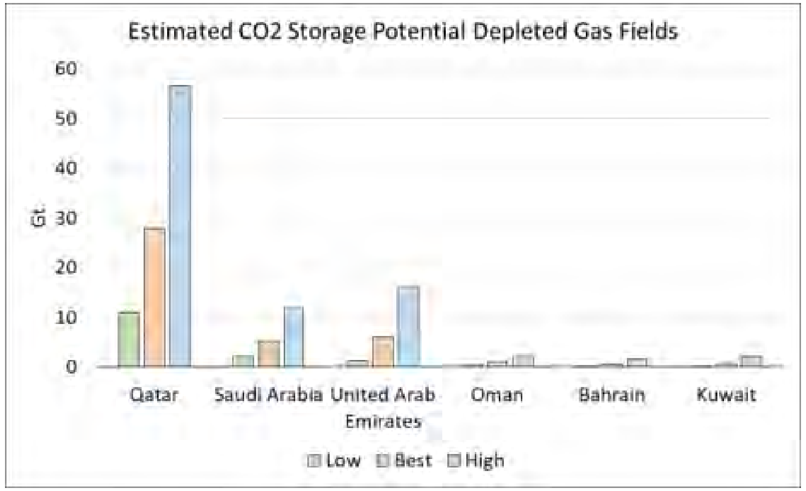
Source: BP, Energy Information Administration (EIA), OPEC, Oher public domain sources

The GCC has the potential to store up to 1 years worth of global carbon emissions in depleted gas reservoirs

CONVERSION OF HC GAS VOLUMES TO CO_2

- Detailed field information is needed to evaluate the suitability of individual reservoirs, which is beyond the scope of this work.
- Based on experience in the region, GaffneyCline has assumed Low case, Best estimate case and High case blanket suitability factors of **30%, 50% and 70%**
- Suitability of depleted gas reservoirs for CCS depends on the following factors:
  - Depth
  - Injectivity
  - Reservoir complexity
  - Containment
  - Source-sink pairing
- **Best estimate 41.5 Gt similar to one year's CO_2 emissions worldwide**
- There is substantial potential CCS capacity in depleted gas reservoirs in the GCC area considering that a 0.1 Gt capacity project is considered major in other pars of the world.

Country	Estimated CO_2 Storage Potential in Depleted Gas Fields (Gt)		
	Low	Best	High
Qatar	11.0	27.9	56.7
Saudi Arabia	2.2	5.2	12.0
United Arab Emirates	1.1	5.9	16.2
Oman	0.4	1.0	2.3
Bahrain	0.2	0.7	1.5
Kuwait	0.1	0.7	2.0
Total	**15.1**	**41.5**	**90.8**



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This potential is not split evenly with Saudi Arabia and UAE having the highest potential given the long term production expected in Qatar

The estimates of storable quantities of CO_2 in depleted and depleting non-associated gas reservoir on the preceding slide show a wide range of uncertainty. This is partly due to sparsity of data, but also largely because of the immaturity of the process of screening, ranking and selecting specific sites for CCS in the region. The next level of detail of analysis requires reliable data from individual fields, which would need to be provided by operators.

Qatar

The estimates of storable quantities for the region is dominated by Qatar, where the supergiant North Field dwarfs all other fields. The North Field is still relatively immature and, at the current production rates, will remain productive for hundreds of years to come. It is therefore unlikely that this field can be considered part of the CCS solution in the foreseeable future. An exception might be if some form of enhanced gas recovery scheme is considered involving CO_2 injection, although from a technical perspective, this seems unlikely.

Saudi Arabia

Saudi Arabia has substantial potential for CCS in depleted gas fields (best estimate case of 5.2 Gt). Saudi Arabia has historically relied on associated gas to fulfill most of its gas requirements. Development of non-associated gas is relatively recent and there is likely to be a long time before the major gas fields are sufficiently depleted to be converted to CCS.

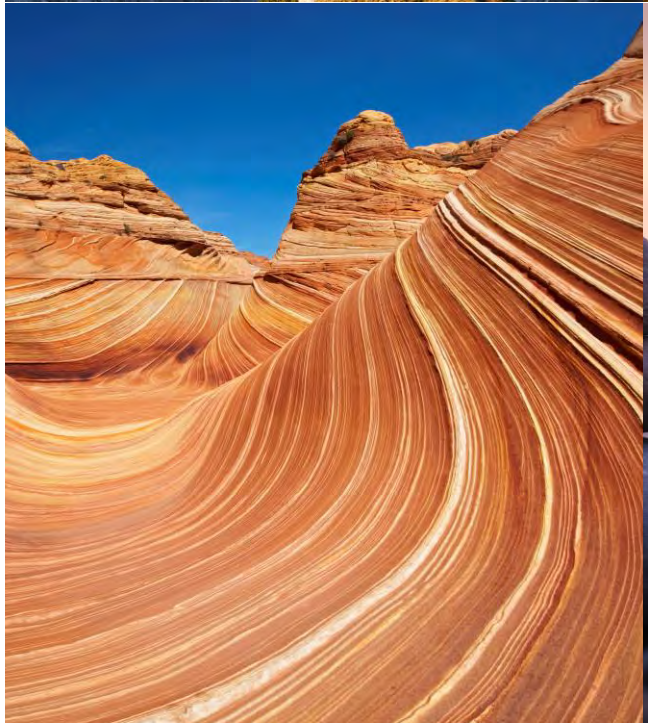
United Arab Emirates

The UAE also has substantial potential for CCS in depleted gas fields (best estimate case of 5.9 Gt). The estimated storage quantities show a wide range of uncertainty, due to large discrepancies in the public domain reported gas resources. This could be because the distinction between associated gas and non associated gas becomes blurred for the multiply stacked reservoirs that contain multiple hydrocarbon types. The UAE has a large number of gas fields with a good mix of mature and immature fields that could provide for shorter term start up and phased CCS projects as gas fields become available.

Oman, Bahrain, and Kuwait

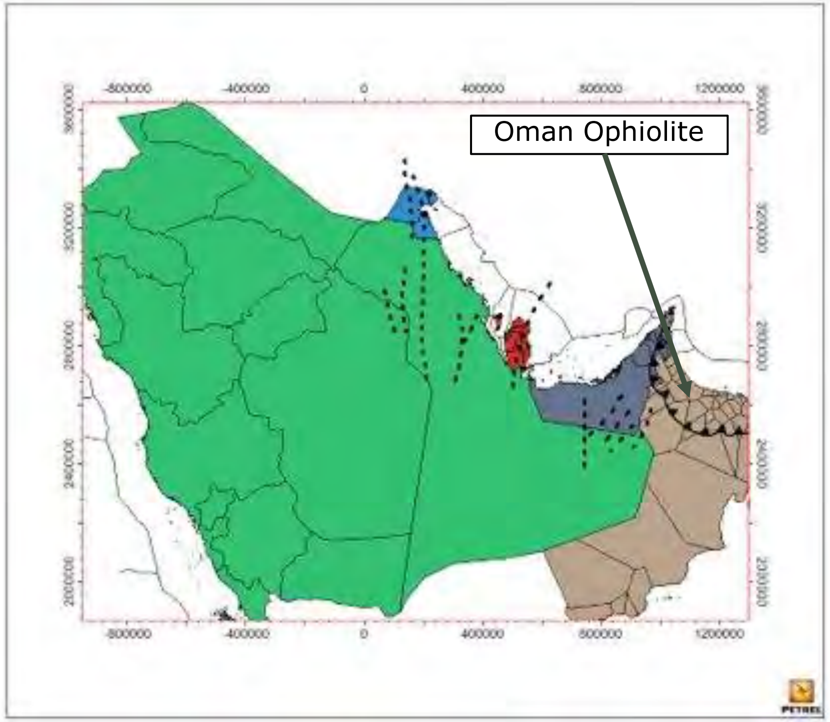
Estimates of storable quantities for these countries are 1 Gt or less. While relatively small compared with others in the region, the estimated storable quantities are still significant, considering that many major projects being considered worldwide target storable quantities less than 0.1 Gt. Bahrain and Kuwait each have a very small number of gas fields, while Oman has a greater portfolio and a good mix of mature and immature developments.

Contents

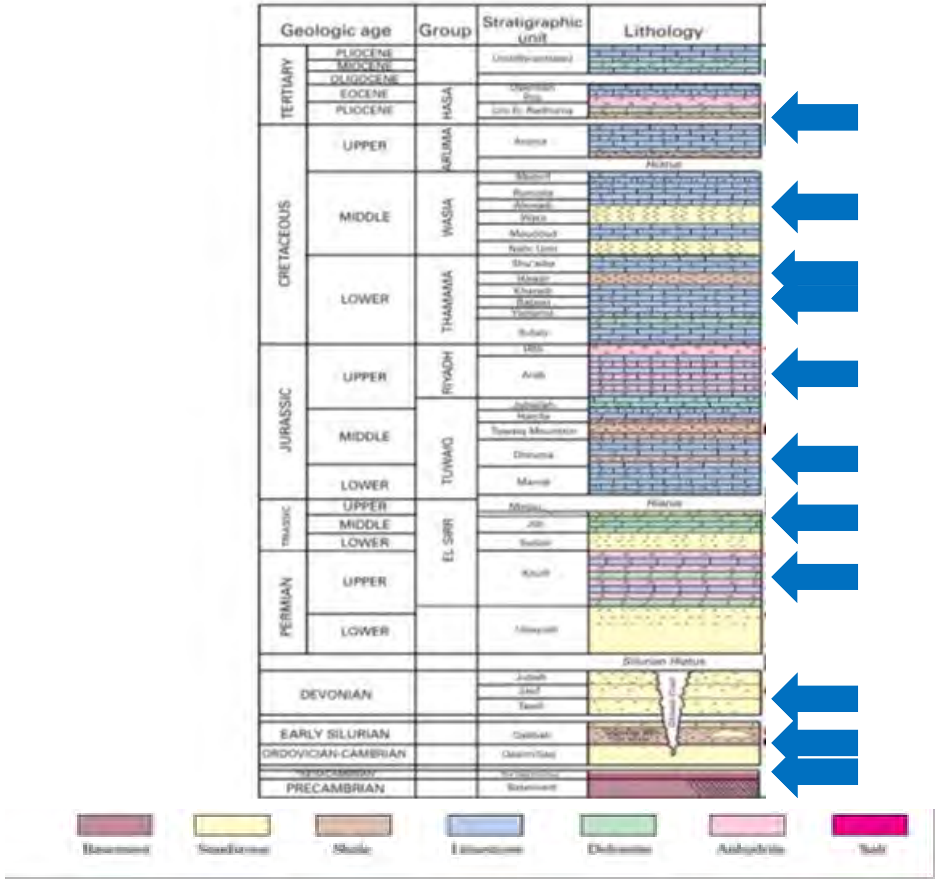


Looking more widely CO_2 storage opportunities in saline aquifers were assessed for 11 sedimentary sequences and the Oman ophiolite

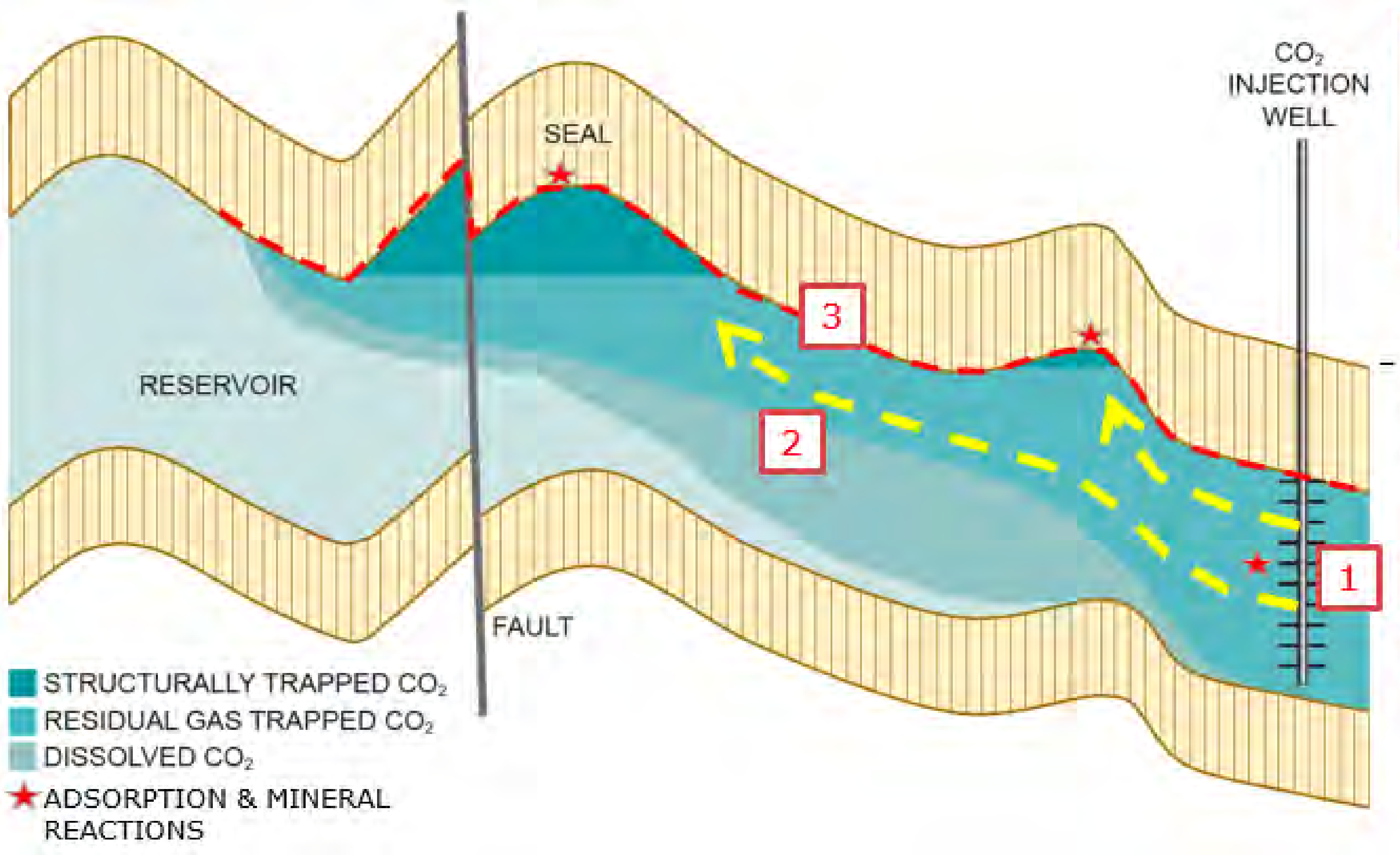
REGION OF INTEREST



REGIONAL STRATIGRAPHIC COLUMN



Saline aquifers require adequate injectivity, storage capacity and high confidence seals



Key issues

1. Injectivity
2. Storage capacity
3. Key containment risks

- Principal controls are:
  - Depth minimum and maximum
  - *(although in some cases deeper target are included with favourable reservoir quality)*
  - Absence of fresh (<10 000ppm TDS) water
  - Optimum reservoir development
  - Regionally extensive and/or multiple seals

Note that "Adsorption and Mineral Reactions" can occur throughout, but are highlighted where especially significant. After National Petroleum Council, 2019. Meeting the dual challenge. A roadmap to at-scale deployment of carbon capture, use and storage.

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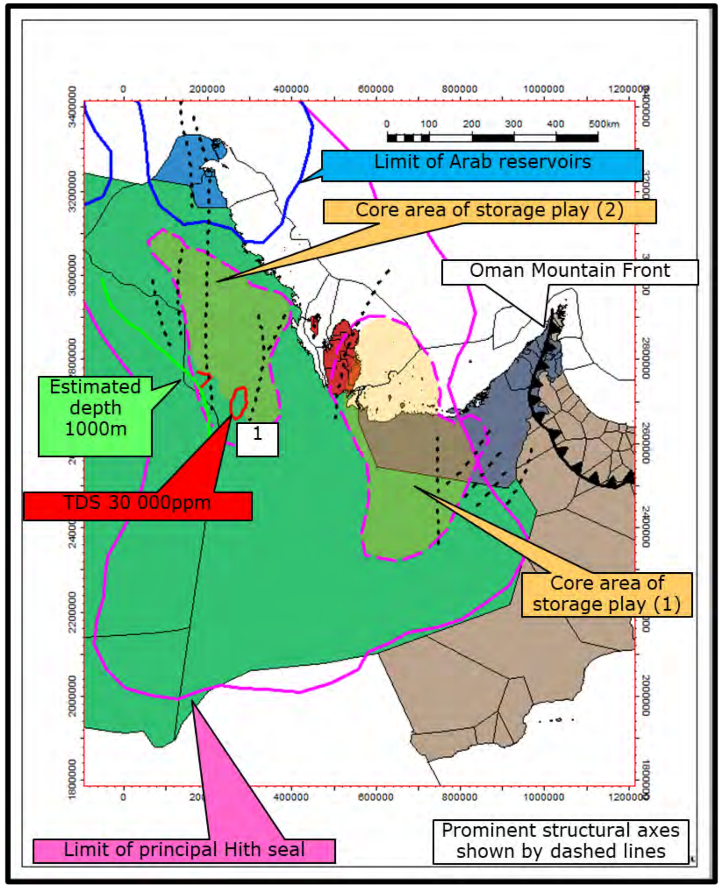
Play Fairway analysis was conducted for each of the 11 sequences producing areas with good storage potential across the GCC

EXAMPLE – THE ARAB SEQUENCE

- Two areas of potential recognised.
- Although Arab reservoirs are widespread, focus is on intrashelf basinal areas, where (i) multiple stacked reservoirs are present, bounded by evaporite seals, and (ii) there is preferential grainstone reservoir development on the margins
- The limits of the overlying Hith Formation seal are not a critical factor, except in far east.
- Depths are variable. A play fairway is recognised in the offshore areas because of the possibility of excellent reservoir quality, despite the greater depth (c. 3500m). In the far west, depths approach the critical 1000m limit.
- No salinity cut-off applies, although fresher waters (approximately 30 000ppm TDS are seen in the west (Note 1).

EXAMPLE STORAGE PLAY FAIRWAY MAP - ARAB



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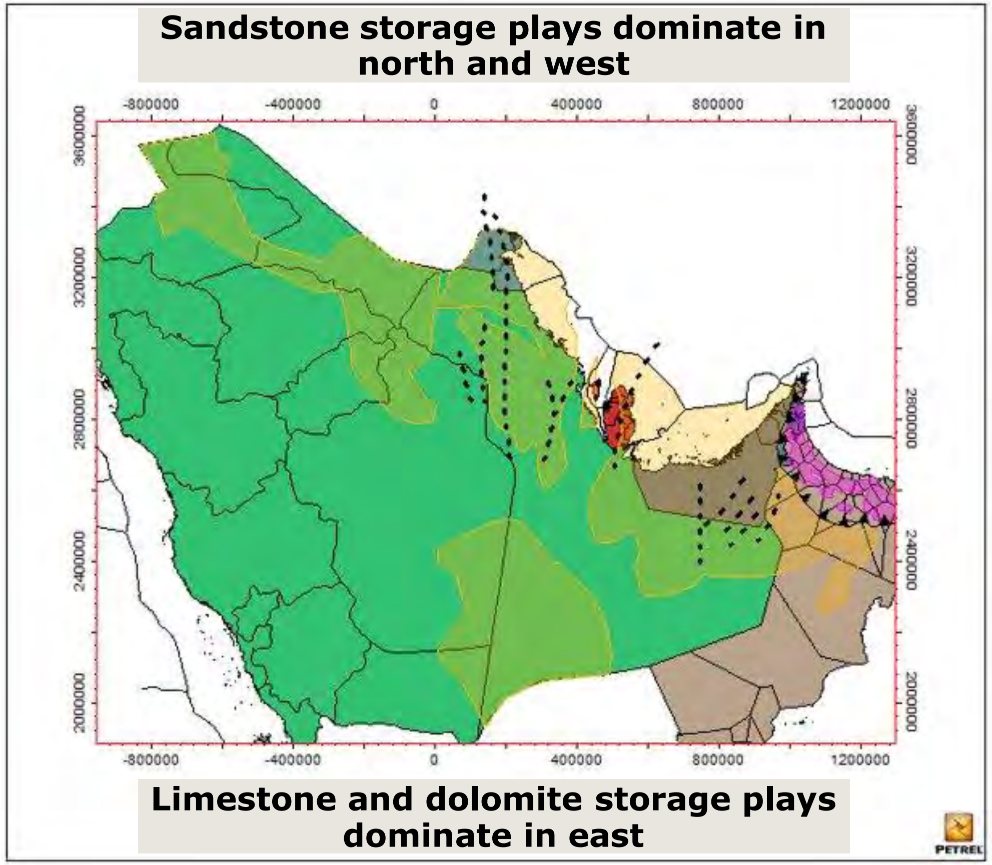
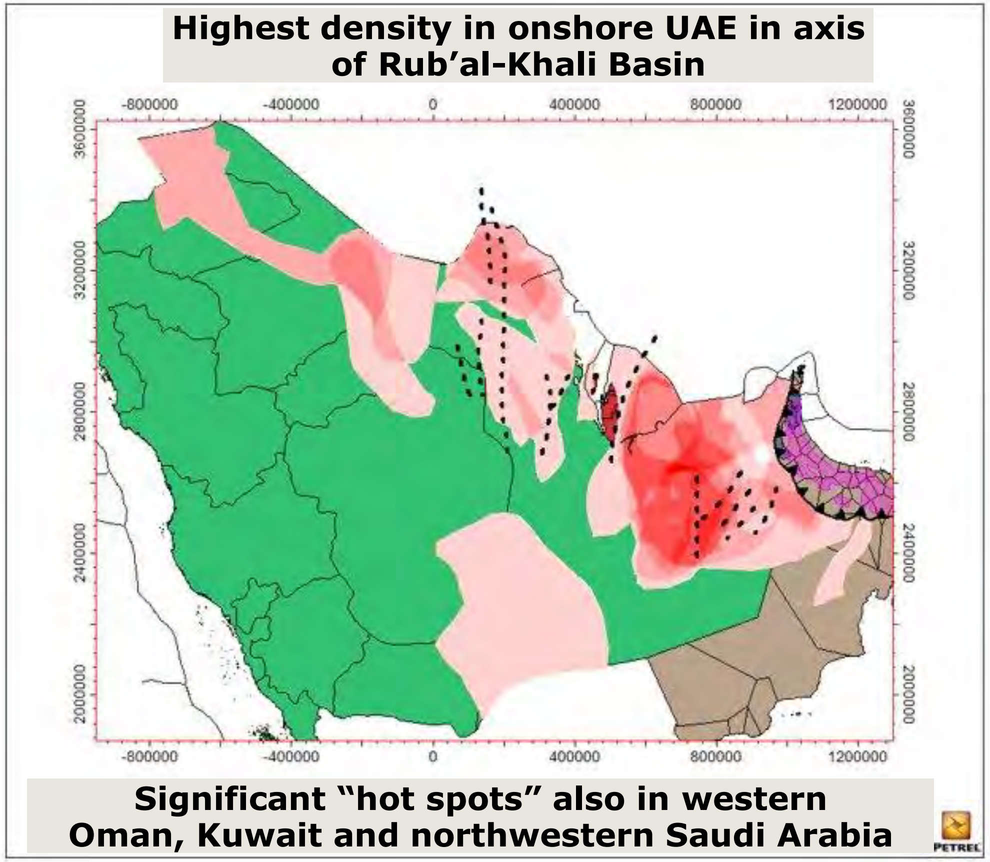
Composite play fairway map for all 11 storage plays includes a number of stacked systems with up to 6 storage plays in one location

COMPOSITE STORAGE PLAY FAIRWAY MAP



DENSITY OF STORAGE PLAY FAIRWAYS INDEPENDENT OF RISK



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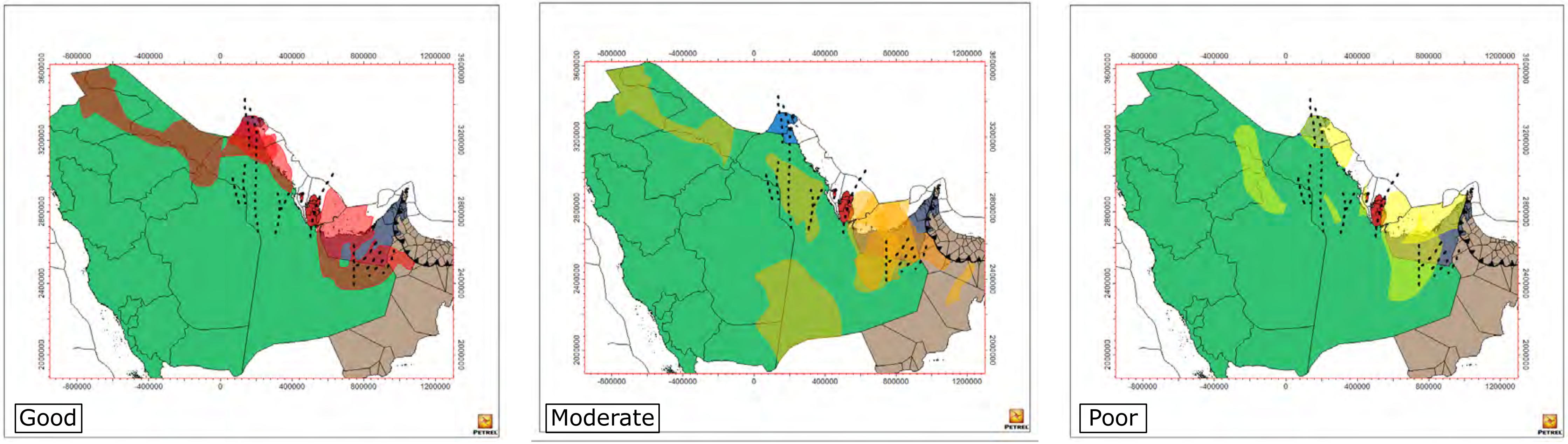
A qualitative risk assessment highlights that sandstones and shallow carbonates offer the best opportunity



- Risks are optimal in well-sealed sandstones and shallow carbonates with proven reservoir trends
- Poorest risks are in deep, tight carbonates – injectivity and uncertain reservoir distribution
- Risk rating addresses overall geological considerations only. Other operational factors such as corrosion, metallurgy, precise requirements of injection, stimulation etc. would need to be addressed in detail scheme design.

Significant saline aquifer storage volume is potentially available in the GCC in addition to depleted gas reservoirs

For each storage play
Range of storage play fairway area
Range of reservoir thickness
Range of reservoir net-to-gross
Range of porosity

Monte Carlo analysis to derive P_{90}, P_{50}, P_{10} for each storage play fairway

Standard assumptions of:

Range of storage efficiency up to 6%

CO_2 density

Summation

Deterministic
Probabilistic

	Storage capacity (Gt)			
Deterministic	**Low**	**Best**	**High**	**Mean**
	39.7	119.3	317.5	155.5
Probabilistic	**P90**	**P50**	**P10**	**Mean**
	108.5	150.1	209.2	155.5

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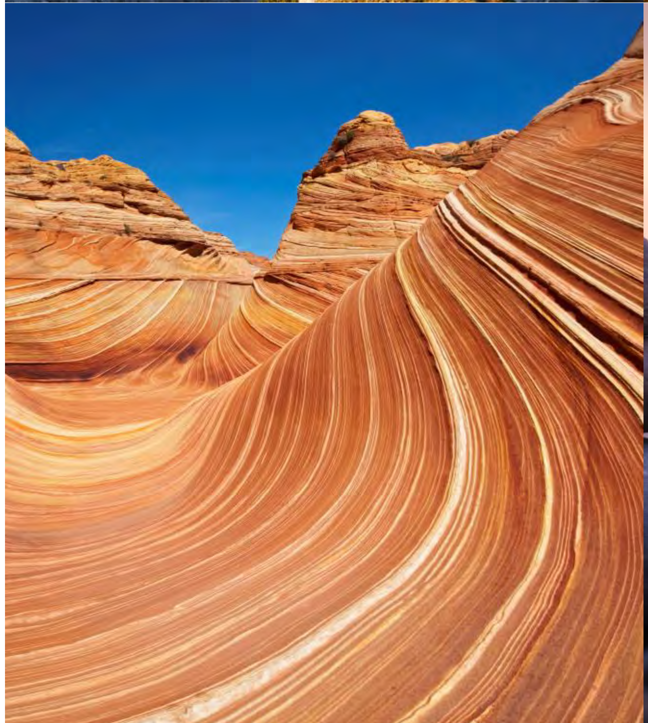


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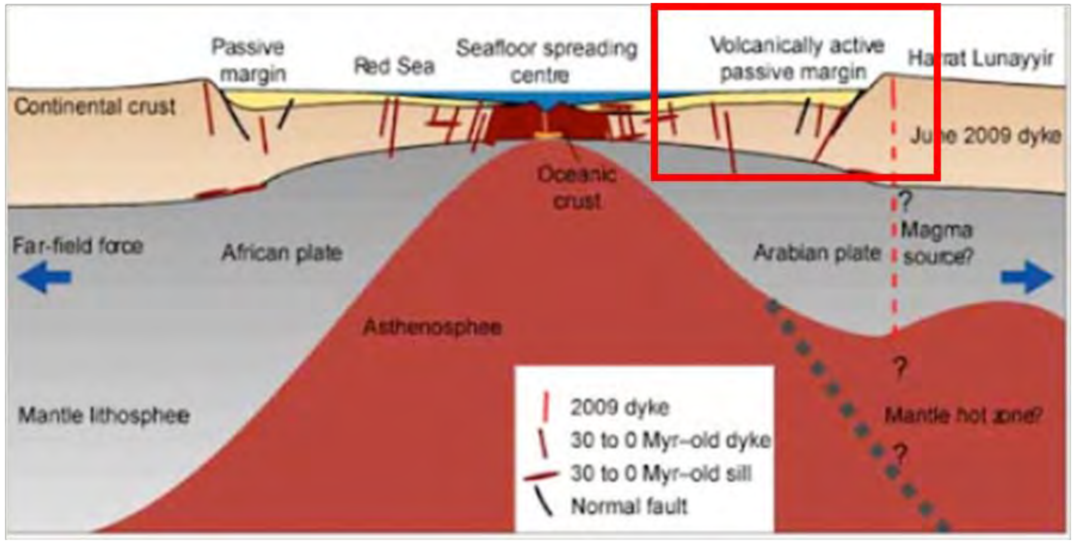
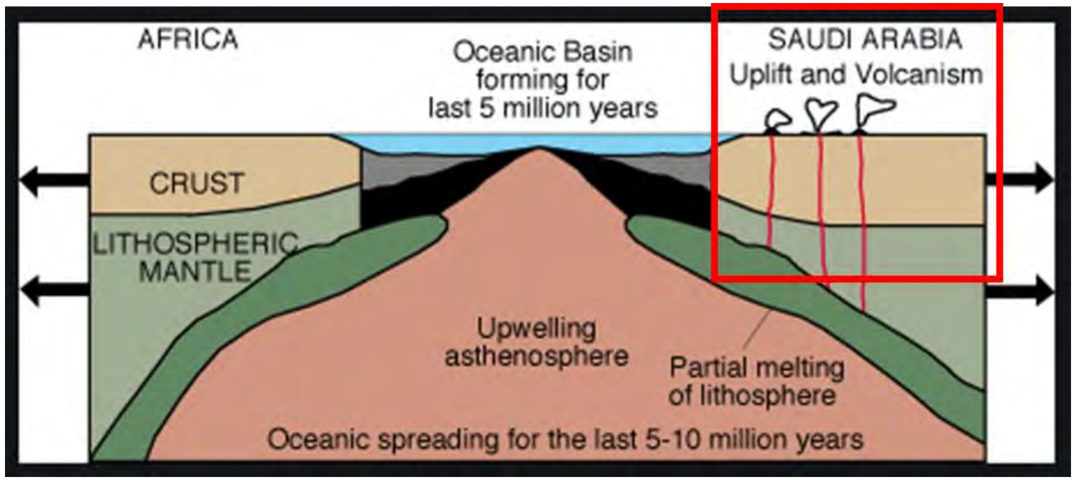
The Red Sea basins are geologically less suitable for carbon storage compared to the formations in the eastern basins of the GCC

LITTLE EVIDENCE FOR AQUIFERS, POSSIBLE SMALL LOCAL SEDIMENTARY PACKAGES



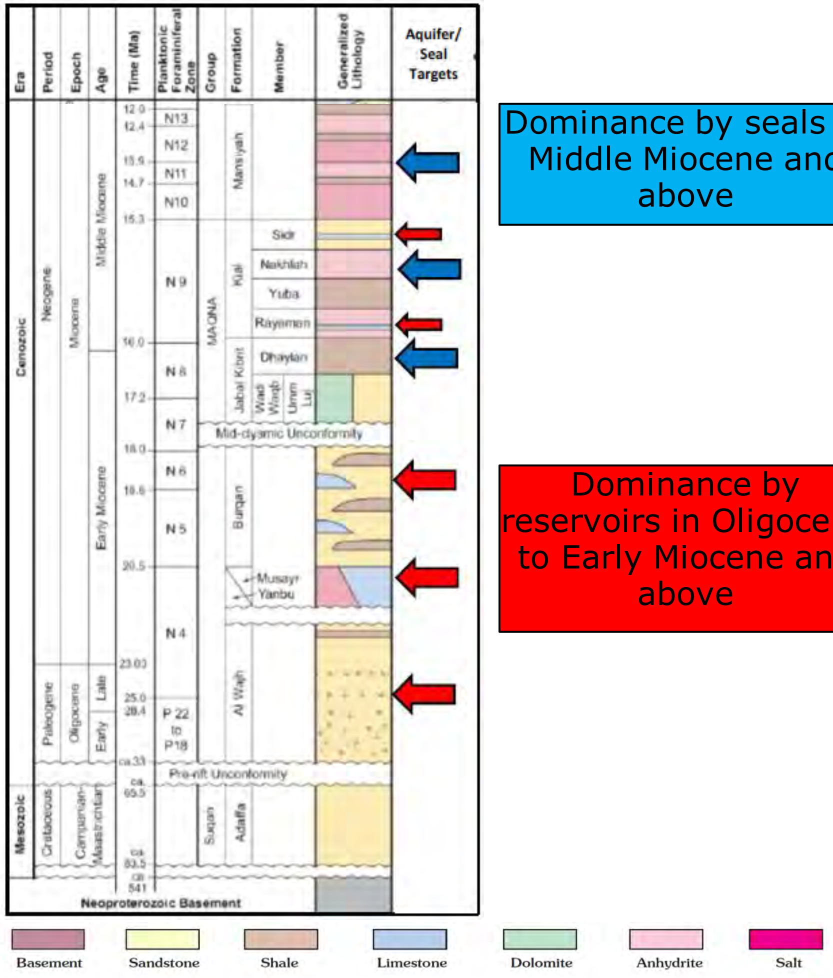
BASEMENT AT SURFACE ALL ALONG COASTLINE EXTENDING HUNDREDS OF KILOMETRES INLAND & ACTIVE VOLCANISM TO THE EAST



The area is not devoid of opportunity but the chance for multiple reservoirs at scale is small

COMMENTARY

- Post Oligocene faulted basins up to 6km thick
- Highly faulted
- Section dominated by continental sandstones in early phase, but by carbonates and evaporites in later phases
- Critical storage play reservoir-seal relationships be absent
- Sedimentary bodies likely small, and seal (top and fault) is critical
- Previous work has concluded that insufficient data available to map targets
- Not considered here an area of sufficient potential at this stage.

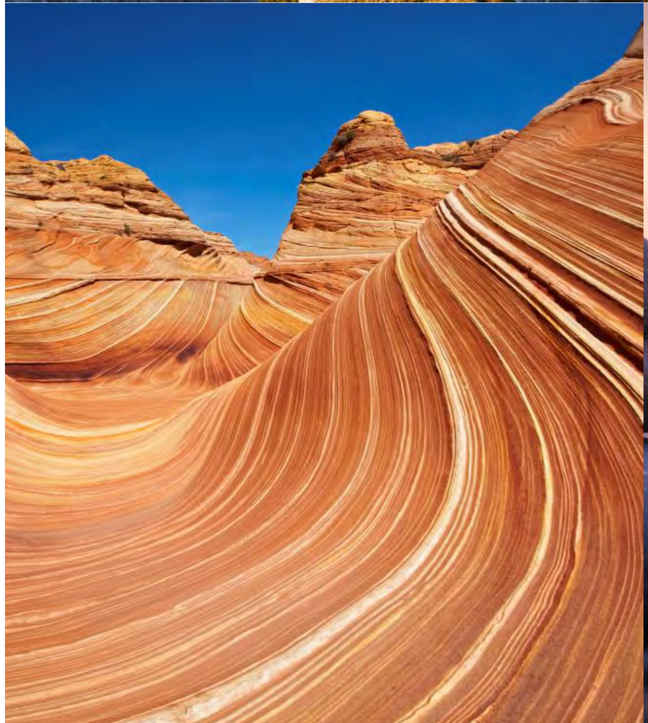


Dominance by seals in Middle Miocene and above

Dominance by reservoirs in Oligocene to Early Miocene and above

Contents



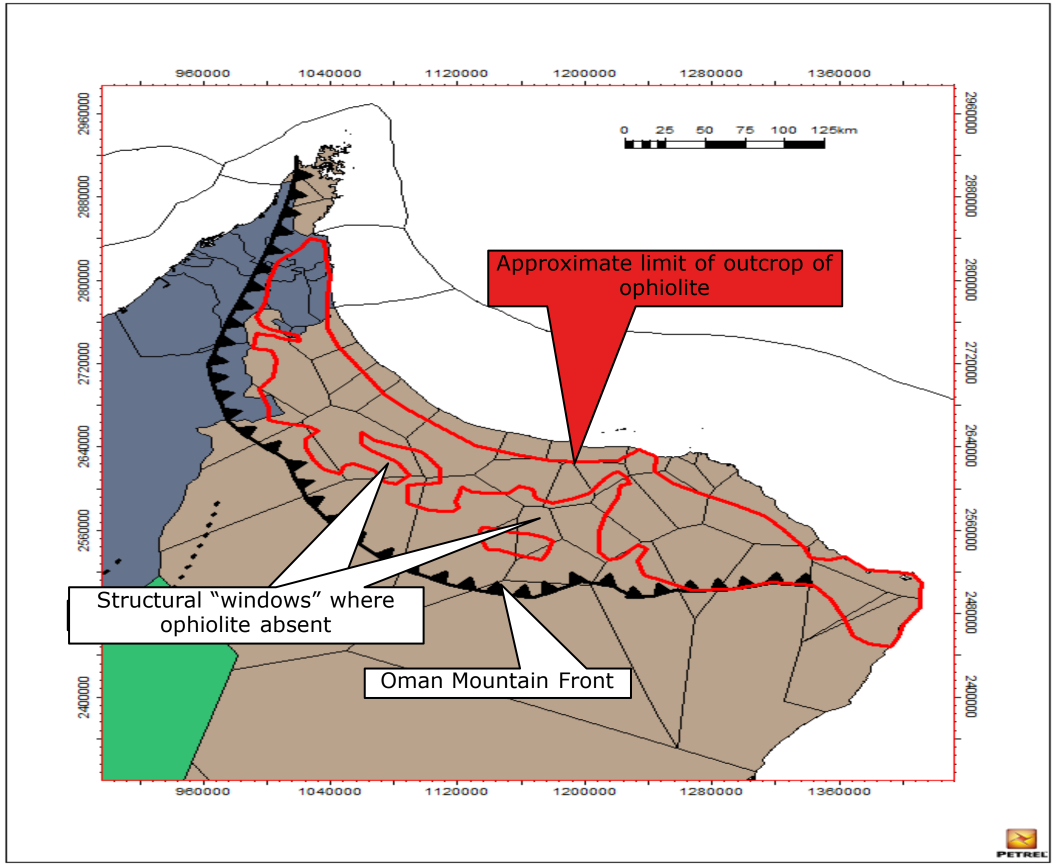



The Oman Ophiolite stores carbon via mineralisation which although inefficient can provide large scale storage

- Ophiolite is thrusted slice of oceanic lithosphere emplaced on the Omani continental margin approximately 90Ma ago
- It contains sections of the Earth's mantle comprising especially reactive mineral suites to CO_2, notably "harzburgites" which contain Mg-rich olivine and pyroxene
- It overlies a major thrust fault and is approximately generally 4.5km thick, but thickness is variable as a result of fault geometry – in places it has been eroded to zero to expose lower layers of crust in "structural windows", but in places is estimated to be over 10km thick.
- Age and exposure at surface mean that it is largely already altered to hydrous "serpentinite" minerals. Estimates of alteration vary between 30-70%. These altered minerals are still susceptible to reaction with CO_2 but hydrous metallic cations are more stable than in the virgin mineral suite. Note that certain reaction pathways yield to volumetric expansion and the generation of fractures that promote reactivity
- Further reaction to CO_2 (carbonation reactions on following slide) is likely to require elevated temperatures >150°C for favourable kinetics. Distribution of hot springs in the Omani Mountains suggests that there are locally high geothermal gradients, but the relationship with the thickness of the ophiolite complex, and whether such temperatures can be achieved in the subsurface, is uncertain.

Although storage efficiency is low there is still sizeable potential for its use as a carbon store

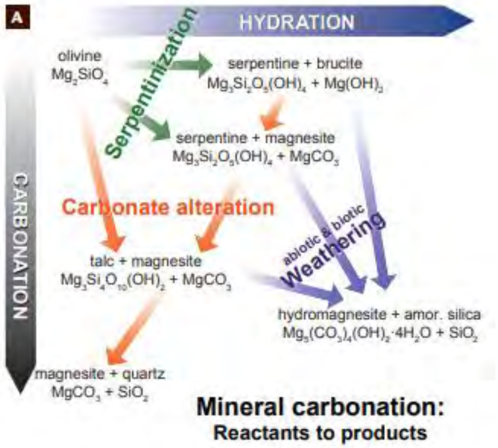
AREAL EXTENT OF THE OMAN OPHIOLITE

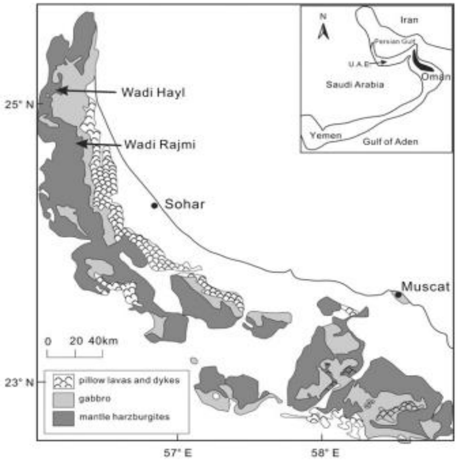


Robinson et al., 2015; Power et al., 2013

DESCRIPTION

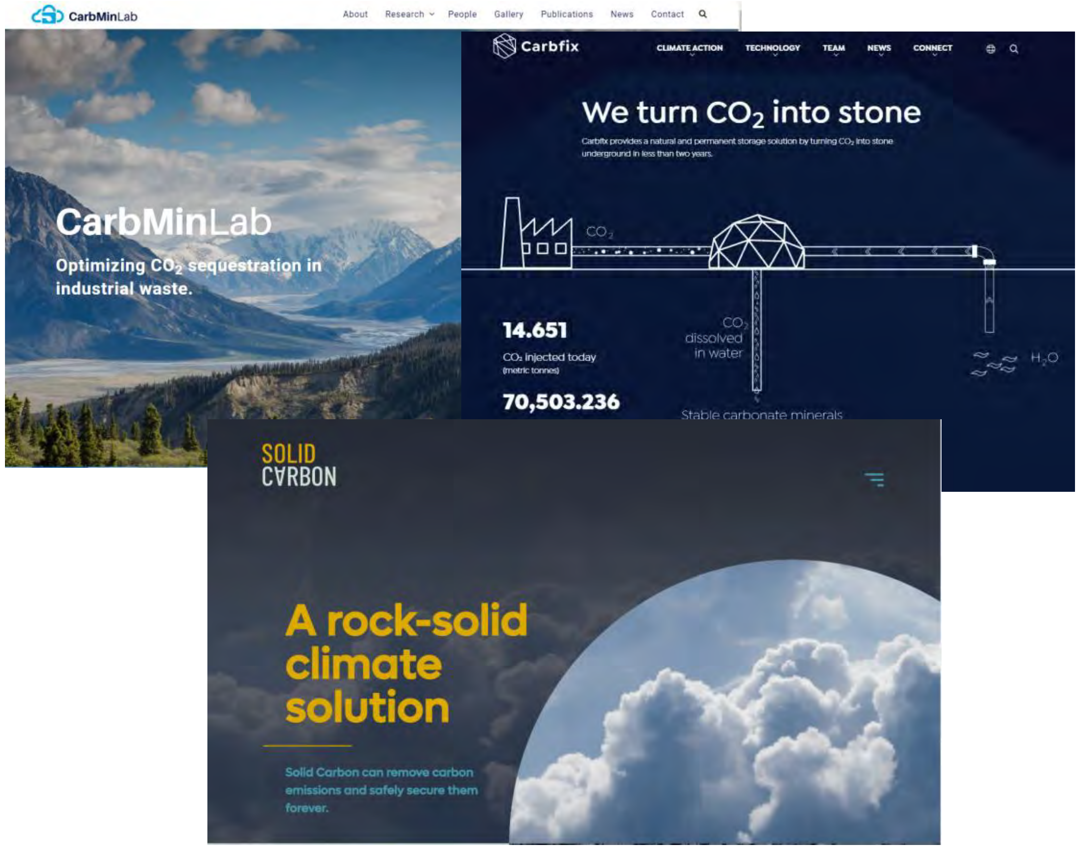
- Detail of rock type distribution. Of particular importance are mantle harzburgites as the most reactive lithology. Note these are not ubiquitous at surface
- Mineral reaction pathways. "Serpentinisation" of virgin mineral suite (1) has largely taken place naturally. Requirement of CO_2 injection is promotion of carbonation reactions (2)
- For the Oman Ophiolite, only 10% storage efficiency is assumed but is still sufficient for **8.2 Gt storage** (areal storage density of 275kt/km²)





The setting of the Oman Ophiolite is comparable to other regions of active CCS research, to store large volumes via mineralisation

ANALOGUE PROJECTS



DESCRIPTION

- Comparable settings to Oman ophiolite are being actively exploited and researched in Iceland, USA, Canada. Examples are illustrated here.
- Projects include:
  - Basalts adjacent to active volcanic centre
  - Deep sea basalts
  - Mafic/Ultramafic rock bodies
  - Mineral tailings from diamond mining (kimberlite) or nickel mining (serpentinite)
- Further work is necessary to integrate conclusions from elsewhere, and details of other ongoing projects are not fully published.
- At present, principal analogue is from Iceland, as the most mature project, and this is used to derive estimates of storage capacity (below). It involves injection and *in situ* storage.
- However, further research could usefully be conducted on using mine tailings projects as potential analogues, with mining of the ophiolite and reaction of CO_2 at surface.

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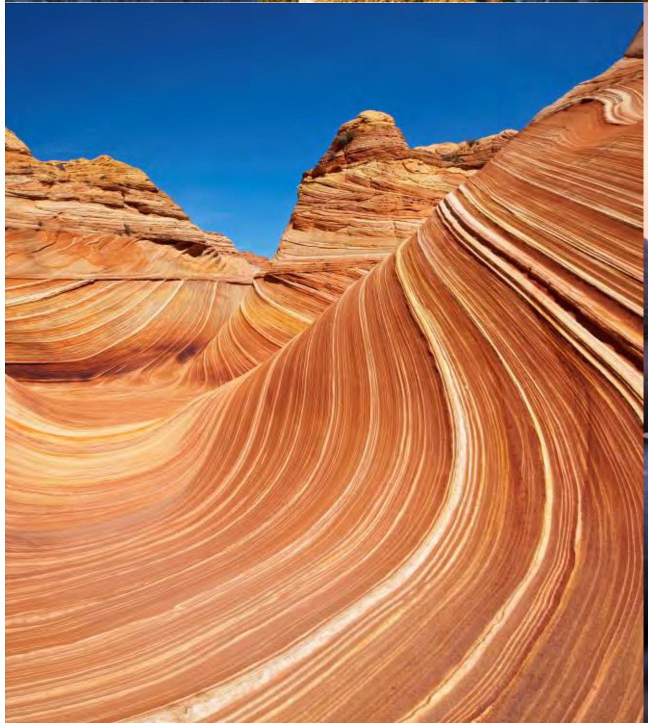
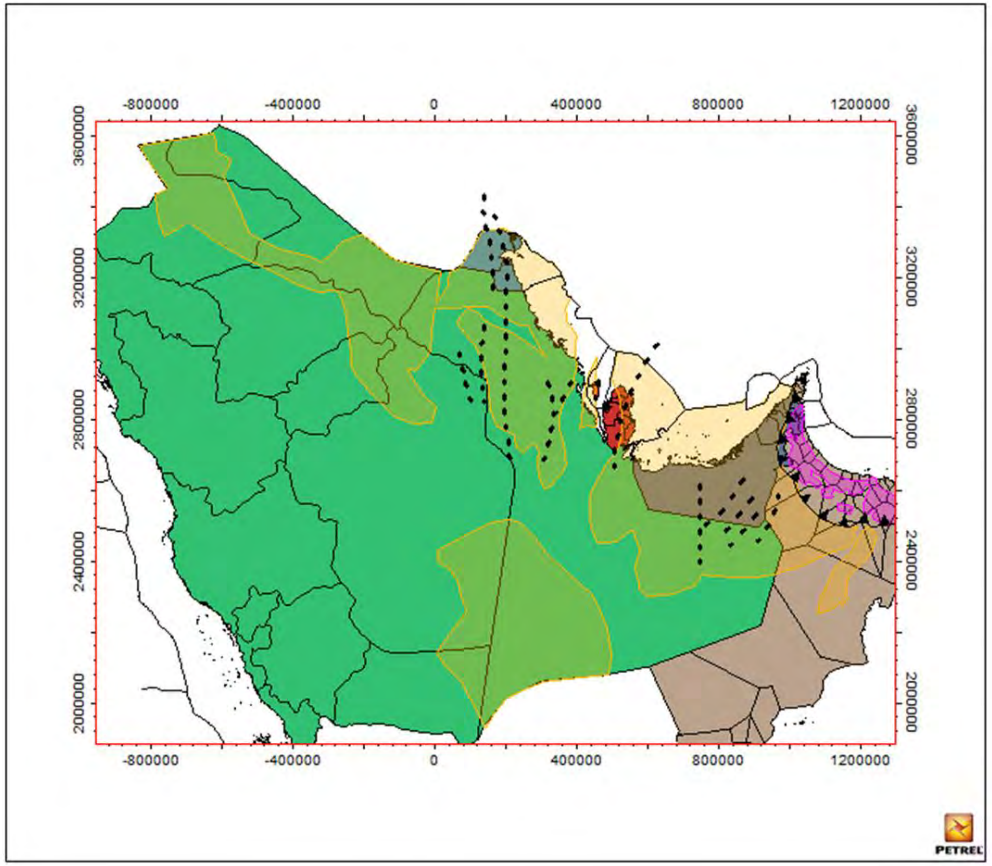



The greatest potential for storage lies in the Rub'al Khali Basin and Oman Ophiolite and a third location centred on Kuwait

CONCLUSIONS - STORAGE

- 11 sedimentary sequences in the Rub'al-Khali Basin and the Oman ophiolite have been screened for potential CO_2 storage reservoir potential
- No significant potential is seen in the Red Sea Basins
- Aggregate storage play fairway (orange) shown on map. All saline aquifers are in the Rub'al-Khali Basin and the northern part of the Arabian Platform
- Principal potential lies in
  - Downdip extensions of Palaeozoic sandstone aquifers in the west and south of Saudi Arabia
  - Cretaceous carbonate reservoirs in the central Rub'al-Khali Basin in the UAE
  - Cretaceous sandstone reservoirs in Kuwait and the north-central Saudi Arabia
- Principal controls on the storage play fairways are:
  - Depth, although in some cases deeper targets are suggested where there is a good chance of favourable reservoir quality
  - Absence of fresh (<10 000ppm TDS) water
  - Optimum reservoir development
  - Regionally extensive and/or multiple seals
- For the Oman Ophiolite (purple), potential is controlled by the presence of suitable lithologies at temperatures sufficiently high for reaction with CO_2

COMPOSITE STORAGE PLAY FAIRWAY MAP



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Storage potential is estimated in the hundreds of gigatons range but more work is required to identify individual storage reservoirs

- At this stage there is huge uncertainty in the volumetric potential, but a provisional Monte Carlo analysis for the Rub'al-Khali storage plays suggests:

Total storage potential (Gtonnes CO_2)		
Low	Best	High
40	119	318

- Excluding those storage plays rated at least in part "poor" yields the following range, suggesting that these could probably be downgraded in future assessment:

Total storage potential (Gtonnes CO_2)		
Low	Best	High
36	109	289

- A single deterministic estimate is made for the Oman ophiolite of 8.2 Gtonnes CO_2

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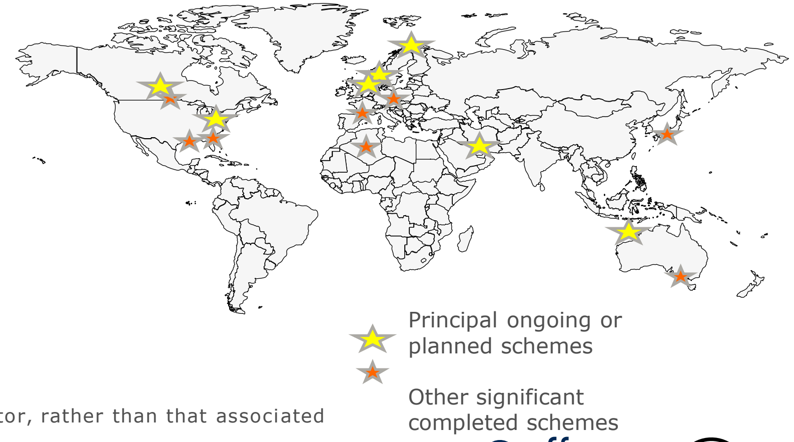
GCC storage compares favourably with global analogues

Project	Country	Start	Rate (Mt/a)	Total reported (Mt)	Unit	Age	Rock type	Depth (m)
Sleipner	Norway	1996	0.85	17	Utsira	Miocene-Pliocene	Sandstone	1000
Snøhvit	Norway	2008	0.7	4	Tubåen	Lower Jurassic	Sandstone	2600
					Stø	Lower Jurassic	Sandstone	2320-2400
Northern Lights	Norway	2024	1.5	-	Johansen	Lower Jurassic	Sandstone	2700
Quest	Canada	2015	1.2	5.7	Basal Cambrian	Cambrian	Sandstone	1900
Illinois Industrial	USA	2017	1		Mount Simon	Upper Cambrian	Sandstone	2150
Gorgon	Australia	2019	4	4.8	Depuy	Upper Jurassic	Sandstone	2000
In Salah	Algeria	2004-2011	1	3.8	Unnamed	Carboniferous	Sandstone	1850
Northern Endurance	UK	2026	4	450*	Bunter	Triassic	Sandstone	1040
Acorn	UK	2024	5		Captain	Cretaceous	Sandstone	2500
Nini	Denmark	2025	Up to 4	4.5	Siri	Paleocene/ Eocene	Sandstone	1700

- The proposed storage plays in the GCC region can be compared positively with some of those currently operational or at an advanced planning stage in other parts of the world.
- Key saline aquifer schemes for comparison are listed in the table. Note this contains prominent active schemes and a selection of those planned.
- Ultimate storage volumes are not widely reported elsewhere, but the rates of CO_2 injection listed, compared to the overall play potential described in this report here, suggest that the scale of opportunity in the CCS area is very significant.



Source: Global CCS Institute, 2020, Bradbury et al., 2021, various other data sources; *Capacity of wider aquifer estimated by operator, rather than that associated with initial scheme

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Carbon capture in the GCC region can be considered world class and in the long term has the potential to import carbon for storage

Aspects	Active schemes globally	Potential in GCC Area
Injectivity	All the prominent schemes propose sandstone reservoirs. Permeabilities in the successful schemes are in the 100-1000mD plus range. Sandstone composition is seen as an issue in places where mineral composition is mixed, leading to CO_2 reactivity. Several schemes are in "rift" hydrocarbon provinces characterised by lateral variation and faulting and this is a distinct problem in maintaining "open system" behaviour.	Sandstone reservoirs are present and these will form the cornerstone of future schemes. They include pure quartzose units which are not expected to react with CO_2. Permeability in sandstones is definitely comparable to those seen elsewhere, but may be lower in limestones and dolomites. However in the optimum reef/build-up facies, higher permeabilities are encountered. There is the possible problem of reactivity of carbonate reservoirs to injected CO_2, and this needs more investigation. Laterally extensive reservoirs in the "passive margin" province are more likely to be characterised by open system behaviour.
Storage capacity	Good schemes are characterised by porosities over 20%, but not exclusively, with some ranging down to 10%. High storage capacity in those schemes with extensive laterally drained reservoirs. High storage efficiency promoted by a certain amount of reservoir heterogeneity, leading to good residual saturation of CO_2.	Porosities in most units is comparable. Good storage efficiency relies on understanding the disposition of reservoir heterogeneity. Carbonate reservoirs may present complications, but it is emphasised that the long history of exploitation of both petroleum and water in the area means that the datasets and understanding of process is probably unparalleled.
Containment	Relies on multiple, regionally extensive top seals, with an understanding of stress regimes and faulting and fracturing.	World-class thick, extensive mudstone, organic-rich limestone and evaporite seals with clear demonstration of their capacity in the established petroleum plays. Faulting is not expected to be a critical aspect of risk.
Storage potential	Largely localised storage play fairways, with in some cases limited potential.	The GCC area presents the possibility of much larger storage potential than is demonstrated by the analogue set of active schemes.

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CHAPTER 4

Hubs Analysis

Contents

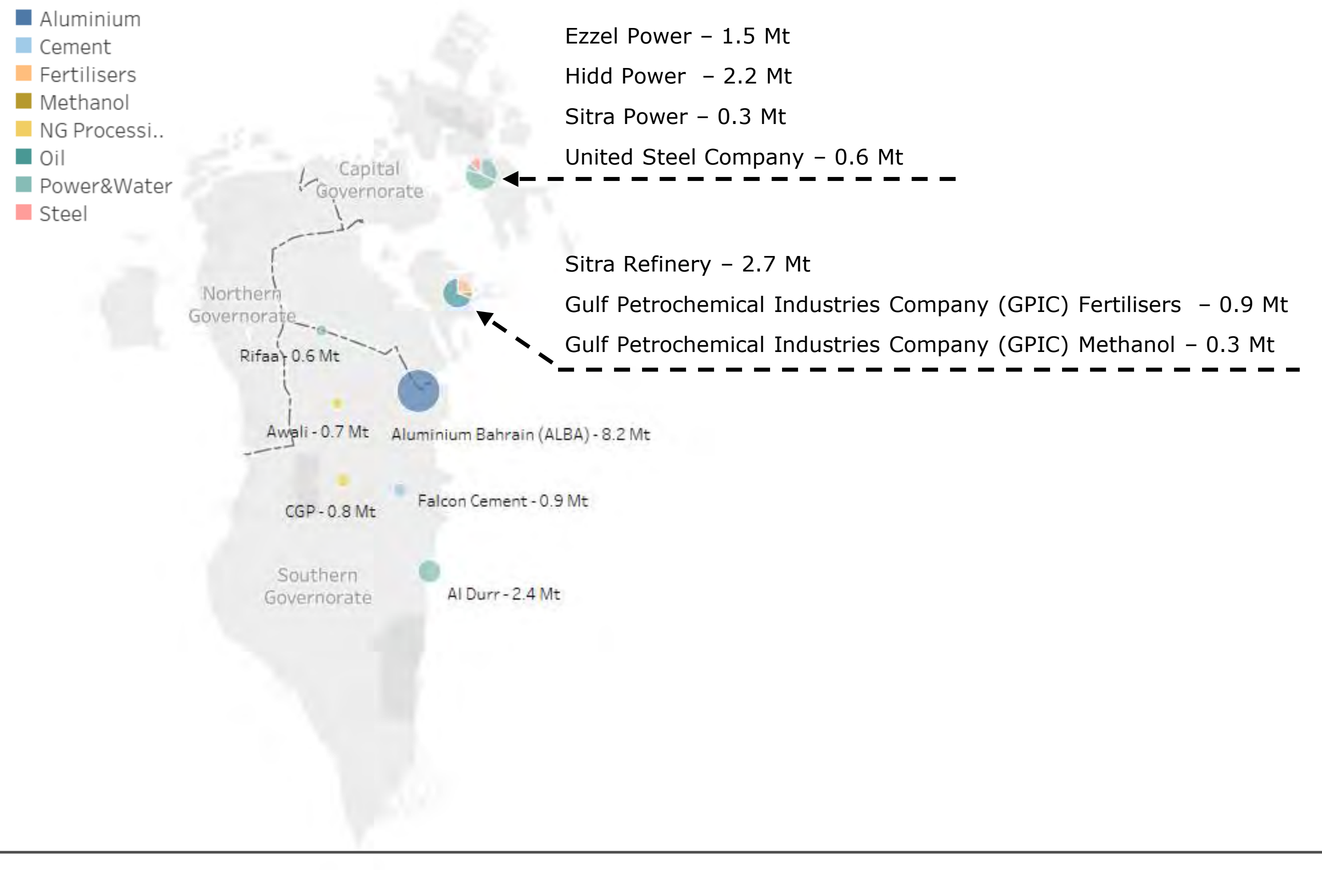



AFRY adopted a specific methodology to analyse the potential for hubs in the GCC based on point sources within a 50km radius of an industrial cluster

- We utilised 2019 historical CO_2 emissions data in our analysis of CCUS hubs
- Each emitting facility is identified as an independent point CO_2 source with a unique longitude and latitude
- CO_2 emissions by power plants are estimated based on their share in each country's generation mix
- CO_2 emissions by other industrial facilities across the remaining sectors are estimated based on their share of installed capacity assuming that they operate as baseload plants
- As part of our initial analysis, each GCC country is assumed to have at least one CCUS hub
- Hubs are defined based on the maximum CO_2 emissions that can be obtained by summing emissions from point sources that fit within a circle with a 50km diameter. This process was performed for each country independently
- CCUS applications in the hubs analysis covers the following industries: cement, aluminium, steel, fertilisers, methanol, oil refining, natural gas processing, LNG, GTL and petrochemicals. Although CCUS applications in existing power & water plants are relatively expensive and complex compared to new build plants, we considered 50% of the emissions from the power & water sector due to its central contribution to overall GCC emissions
- To refine the analysis, we can impose a lower CO_2 emissions limit to consider the region enclosed by the 50km diameter circle a hub ~ 20 Mtpa and above

Bahrain could host one hub based on the number of industrial clusters in the northeast of the country but emissions are small by GCC standards

BAHRAIN CO_2 EMISSIONS IN 2019 – 22 Mt



DESCRIPTION

- The majority of Bahrain's CO_2 emissions are driven by its active aluminium smelting and power generation industries
- In 2020, the installed power capacity was approximately 4 GW whereas Aluminium Bahrain (ALBA) operated 3.7 GW of captive power
- CO_2 emissions are concentrated in the north-eastern part Bahrain in the cities of Hidd, Sitra, and Askar which seems the most likely region for a domestic hub
- Fertilisers and methanol are the easiest and lowest capture cost industries in Bahrain, followed by oil refining, steel, power generation, and aluminium
- Bahrain's captured CO_2 emissions could potentially be directed to Qatar or Jubail as the country does not have direct access to known geological storage and has low volumes of depleted gas reservoirs

Source: AFRY analysis

Aluminium smelting and power generation account for the majority of Bahrain's CO_2 emissions and are clustered in the north-eastern region

Electricity generation

- Power Plants: Rifaa, Hidd, Ezzel, Sitra, Al Durr

Oil & gas activities

- Oil refineries: Sitra BAPCO
- Natural gas processing: CGP, Awali

Metals production

- Aluminium: Aluminium Bahrain (ALBA)
- Steel: United Steel Company B.S.C

Cement

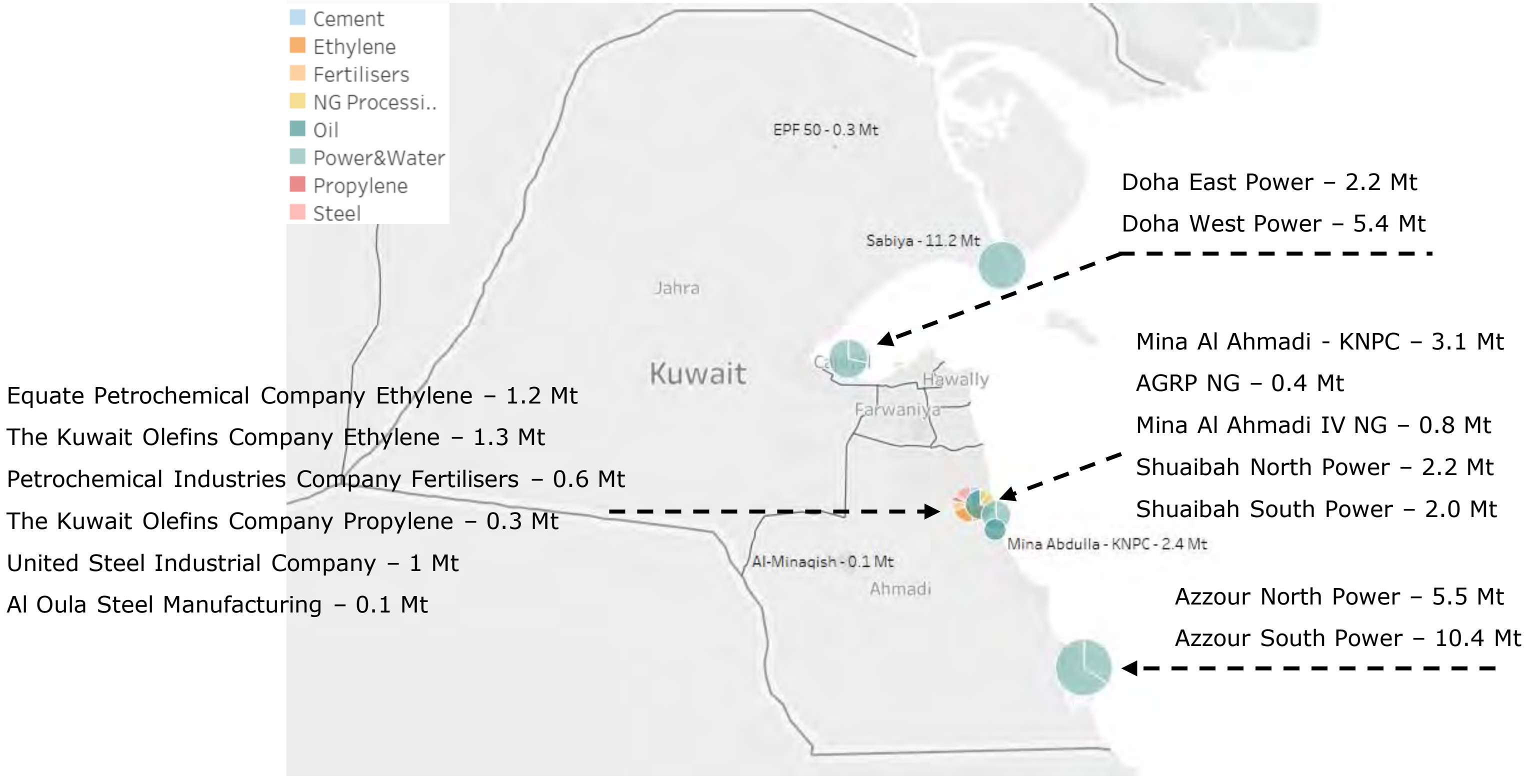
- Cement plants: Falcon Cement

Chemical production

- Fertilisers: Gulf Petrochemical Industries Company (GPIC)
- Methanol: Gulf Petrochemical Industries Company (GPIC)

Kuwait could support an east coast hub, however its relatively small emissions and distance from neighbouring clusters are challenging

KUWAIT CO_2 EMISSIONS IN 2019 – 52 Mt



DESCRIPTION

- Easy and low capture cost industries are clustered in the city of Shuaiba, although the capacities are small to form a hub without being combined with neighbouring gas processing plant and oil refineries
- Oil-fired generation constituted 40% of Kuwait's power generation capabilities in 2020 making it the second largest after Saudi Arabia
- Power plants are spread over Kuwait's east coast with the largest units operating in the far northern and southern regions
- Kuwait is the farthest country from Rub'al-Khali geological storage and Oman Ophiolite. CO_2 emissions could however be directed to Jubail which is the closest potential hub to Kuwait

Source: AFRY analysis

Kuwait's CO_2 emissions stem largely from the power sector and to a lower extent from oil refining, and are concentrated on the country's east coast

Electricity generation

- Power Plants: Shuwaikh, Shuaiba North, Shuaibah South, Doha East, Doha West, Azzour North, Azzour South, Sabiya

Oil & gas activities

- Oil refineries: Mina Abdulla KNPC, Mina Al Ahmadi KNPC
- Natural gas processing: AGRP Mina Al Ahmadi, Al Minagish, EPF 50

Metals production

- Steel: Al Oula Steel Manufacturing Company K.S.C, United Steel Industrial Company K.S.C

Cement

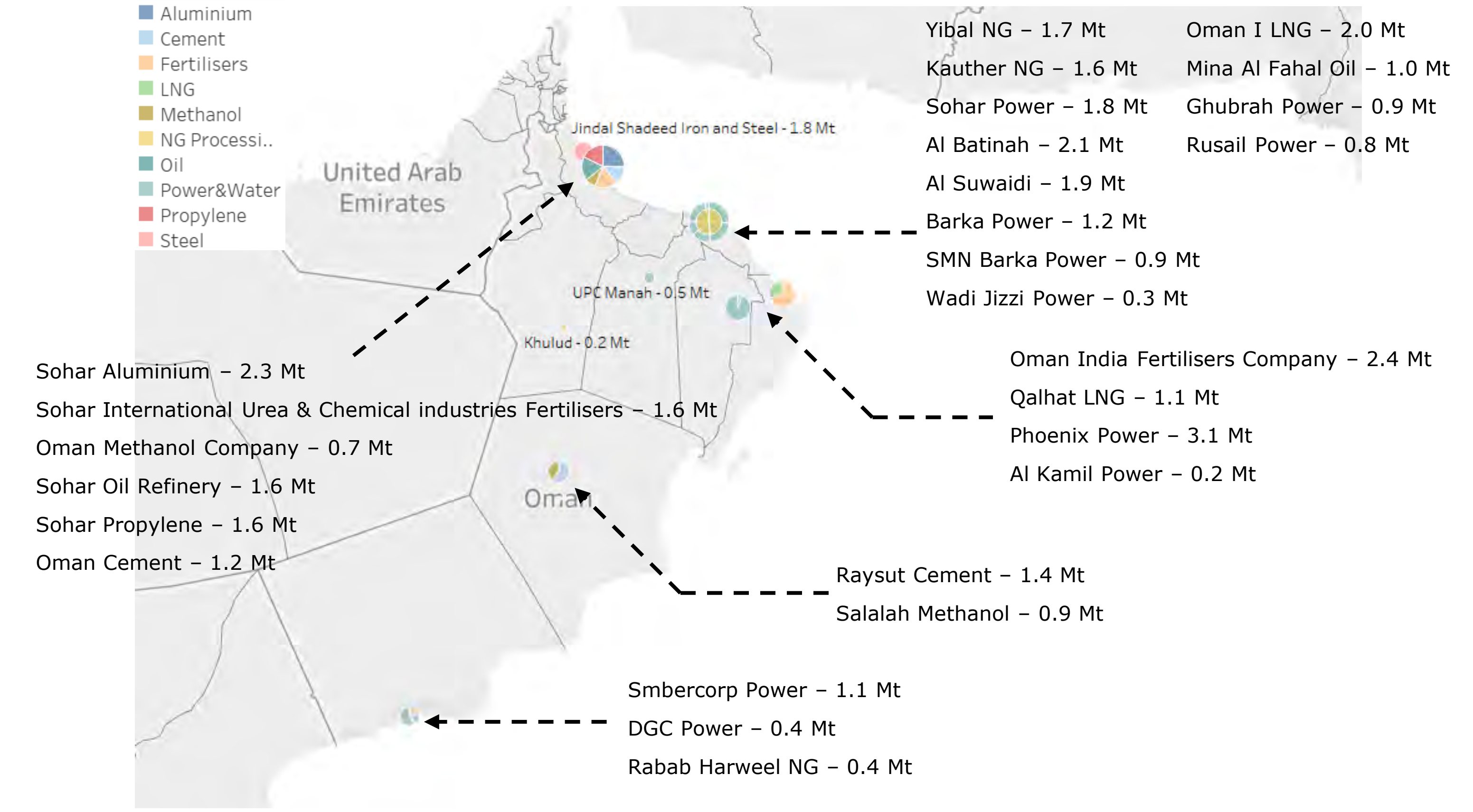
- Cement plants: Kuwait Cement Company

Chemical production

- Fertilisers: Petrochemical Industries Company K.S.C
- Ethylene: The Kuwait Olefins Company, Equate Petrochemical Company
- Propylene: The Kuwait Olefins Company

Northern Oman has potential for a hub based on imports but is less suitable as a regional hub in the GCC compared to larger clusters nearby

OMAN CO_2 EMISSIONS IN 2019 – 39 Mt



DESCRIPTION

- Muscat Governorate and its neighbouring regions are home to several low capture cost industries like natural gas processing, fertilisers, methanol, and other petrochemicals
- Power plants are concentrated in northern Oman in proximity to demand centres whereas Salalah in the south is less active
- A potential hub could be formed between the northern clusters with a diversified portfolio of industries
- Northern Oman has direct access to the Oman Ophiolite which is estimated to have a tentative carbon storage capacity of 8.2 $GtCO_2$ and can serve Oman for a long period. The challenge with this approach revolves around the storage efficiency of the Oman Ophiolite due to the porosity of the formations.

Source: AFRY analysis

Northern Oman has active petrochemical, NG processing, and power sectors condensed around Muscat Governorate, while the south has lower potential

Electricity generation

- Power Plants: Al Kamil, Phoenix, UPC Manah, DGC, Smbercorp, RAEC SOAC, Ghubrah, Rusail, Al Batinah, PWP, Sohar, Wadi Jizzi, Barka, Al Suwaidi, SMN Barka

Oil & gas activities

- Oil refineries: Mina Al Fahal ORPC, Sohar ORPC
- Natural gas processing: Khulud, Yibal, Zauliyah, Rabab Harweel, Kauther
- LNG: Oman I, Qalhat

Metals production

- Aluminium: Sohar Aluminium
- Steel: Jindal Shadeed Iron & Steel

Cement

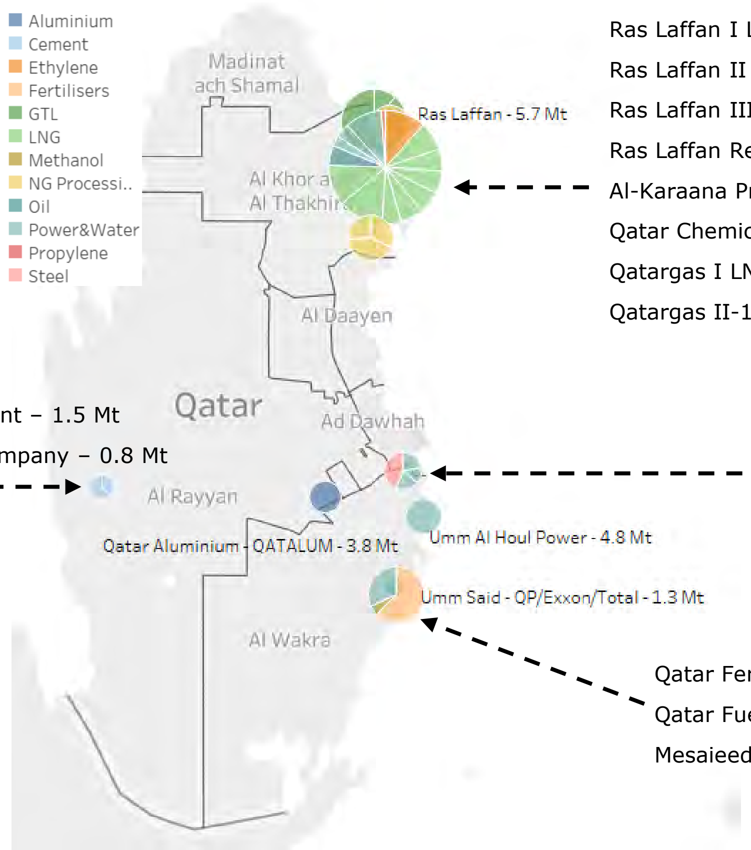
- Cement plants: Raysut Cement, Oman Cement

Chemical production

- Fertilisers: Oman India Fertiliser Company SAOG, Sohar International Urea & Chemical Industries
- Methanol: Oman Methanol Company, Salalah Methanol Company
- Propylene: Sohar Propylene (Sohar refinery)

Qatar has the potential to operate two of the largest CO_2 source hubs in the GCC region driven by natural gas processing and liquefaction, and GTL

QATAR CO_2 EMISSIONS IN 2019 – 108 Mt



Ras Laffan I LNG – 2.6 Mt
Ras Laffan II LNG – 6.3 Mt
Ras Laffan III LNG – 5.7 Mt
Ras Laffan Refinery – 2.7 Mt
Al-Karaana Propylene Plant - 0.6 Mt
Qatar Chemical Company - 5.6 Mt
Qatargas I LNG – 4 Mt
Qatargas II-1 LNG – 3.1 Mt

Qatargas II-2 LNG – 3.1 Mt
Qatargas III LNG – 3.1 Mt
Qatargas IV LNG – 3.1 Mt
Pearl NG – 2.0 Mt
Al Khaleej NG – 2.5 Mt
Dolphin NG – 3.1 Mt
Pearl GTL – 14.6 Mt
Oryx GTL – 1.8 Mt

Qatar National Cement – 1.5 Mt
Al Khaliji Cement Company – 0.8 Mt

Qatar Steel Company – 2.3 Mt
Ras Abu Fontas B – 3.0 Mt

Qatar Fertilisers Company – 7.4 Mt
Qatar Fuel Additives Company Methanol – 0.7 Mt
Mesaieed Power – 3.8 Mt

DESCRIPTION

- Active natural gas processing, LNG, and GTL plants operate in Northern Qatar contributing to more than 50 $MtCO_2$ emissions per annum
- The northern hub in Qatar could become the second largest in the GCC region after Jubail
- In addition, Qatar has a number of petrochemical, fertilisers, aluminium and refineries in the southern region of its east coast which could potentially comprise a second hub
- Qatar shares a boarder with Saudi Arabia and could potentially be given direct access to Rub’al-Khali or clustered with Jubail hub
- On the very long term, captured CO_2 emissions could be stored in depleted gas reservoirs. This option becomes significant once the North Field is utilised for this purpose, however, currently it is projected to be operational hundreds of years yielding this path unrealistic for short to medium term developments

Source: AFRY analysis

Large domestic CO_2 point sources from GTL, LNG and natural gas processing favour a hub, but storage may not be available in the short term

Electricity generation

- Power Plants: Ras Abu Fontas B, Ras Abu Fontas B1, Ras Abu Fontas B2, Ras Laffan A, Ras Laffan B, Ras Laffan C, Mesaieed Power, Umm Al Houl Power

Oil & gas activities

- Oil refineries: Ras Laffan refinery, Umm Said refinery
- Natural gas processing: Ras Laffan NG processing, Dolphin, Al Khaleej, Pearl
- LNG: Ras Laffan I,II,III and Qatargas I, II-1,II-2, III, IV
- GTL: Pearl GTL, Oryx GTL

Metals production

- Aluminium: Qatar Aluminium
- Steel: Qatar Steel Company Q.S.C

Cement

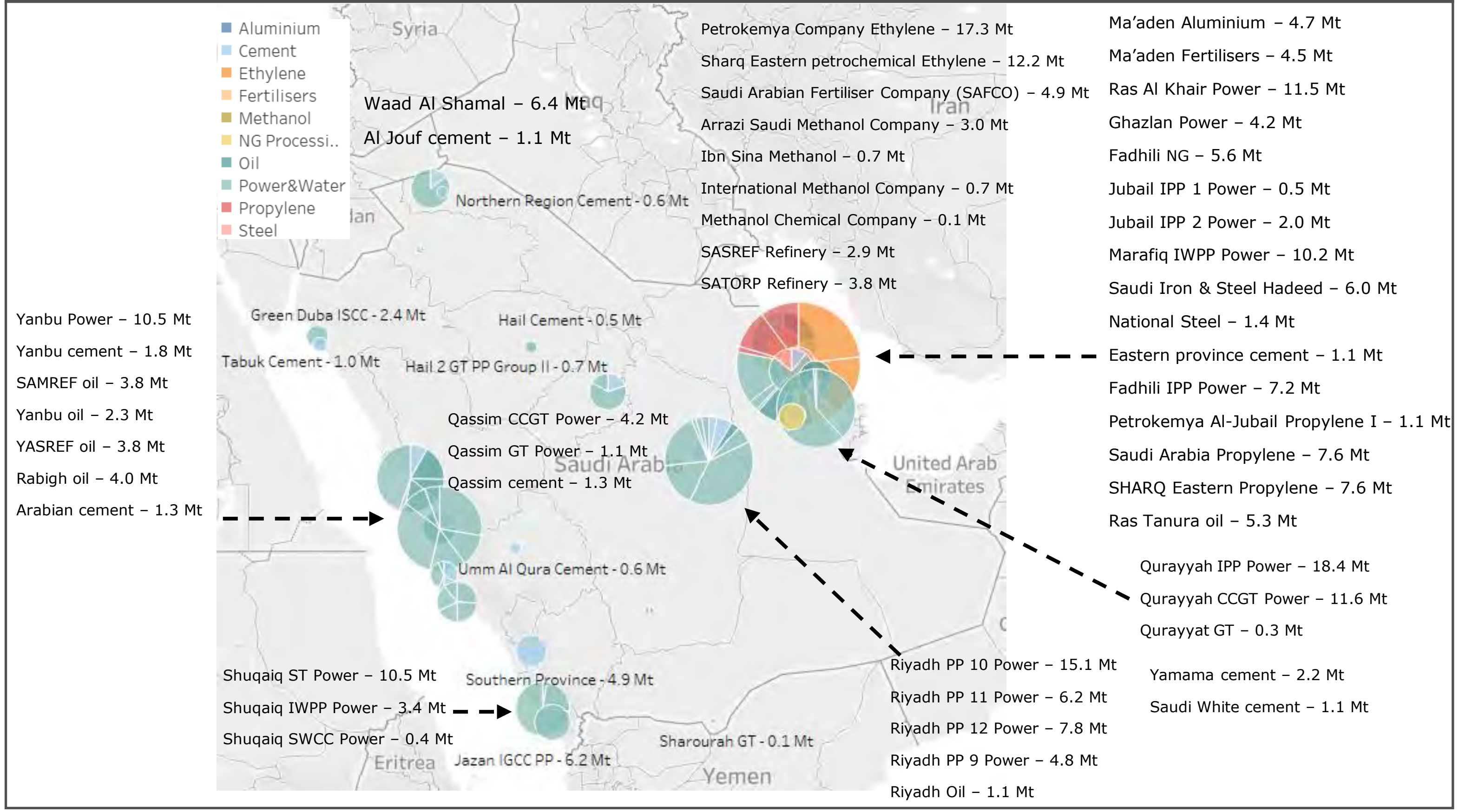
- Cement plants: Qatar National Cement, Al Khaliji Cement Company

Chemical production

- Fertilisers: Qatar Fertiliser Company
- Methanol: Qatar Fuel Additives Company
- Ethylene: Qatar Chemical Company
- Propylene: Al-Karaana Ras Laffan Propylene Plant

Saudi Arabia has the potential to construct two large CCUS hubs as recently announced in the country's updated NDC

SAUDI ARABIA CO_2 EMISSIONS IN 2019 – 324 Mt



DESCRIPTION

- Saudi Arabia could potentially operate two CCUS hubs in Jubail on the east coast and Yanbu on the Red Sea coast
- Jubail hub has more diverse industries including fertilisers, methanol, petrochemicals, oil refineries, natural gas processing, aluminium, steel, and power plants. Jubail is projected to become the largest CCUS hub in the GCC region
- Yanbu hub is predominantly comprised of power plants and oil refineries
- The central region in Riyadh has a number of power plants with emissions exceeding 30 $MtCO_2$ per year but issues on connectivity and land availability around the Saudi capital
- Potential hubs in Saudi Arabia have a huge competitive advantage because they have direct access to Rub'al-Khali and Red Sea Basin saline aquifers

Source: AFRY analysis

Large domestic point sources coupled with adjacent clusters in other GCC countries give Saudi Arabia a competitive advantage to set up hubs

Electricity generation

- Power Plants: Fadhili, Green Duba, Marafiq JWAP, Qassim CCGT, Qurayyah CCGT, Qurayyah IPP, Rabigh 2, Riyadh PP8, Riyadh PP9, Riyadh PP10, Riyadh PP11, Riyadh PP12, Ras Al Khair, Waad Al-Shamal, Ghazlan, Jubail IPP 1, Jubail IPP 2, Al Khobar 2, Al Khobar 3, Al Jouf, Faras GT, Hail 2, Jeddah, Juba PP, Qassim GT, Qurayyah GT, Rabigh GT, Sharourah GT, Tohama Oil PP, Wadi Al Dawasir, Jazan IGCC, Jeddah South, Rabigh 1, Rabigh 2, Rabigh ST, Shuaibah PP, Shuqaiq, Jeddah PP SWCC, Al Shuaibah SWCC, Shuqaiq SWCC, Yanbu SWCC

Oil & gas activities

- Oil refineries: Rabigh, Ras Tanura, Riyadh, SAMREF, SASREF, SATORP, Yanbu, YASREF
- Natural gas processing: Shedgum, Fadhili

Metals production

- Aluminium: Ma’aden
- Steel: Saudi Iron & Steel Company (Hadeed), National Steel Company

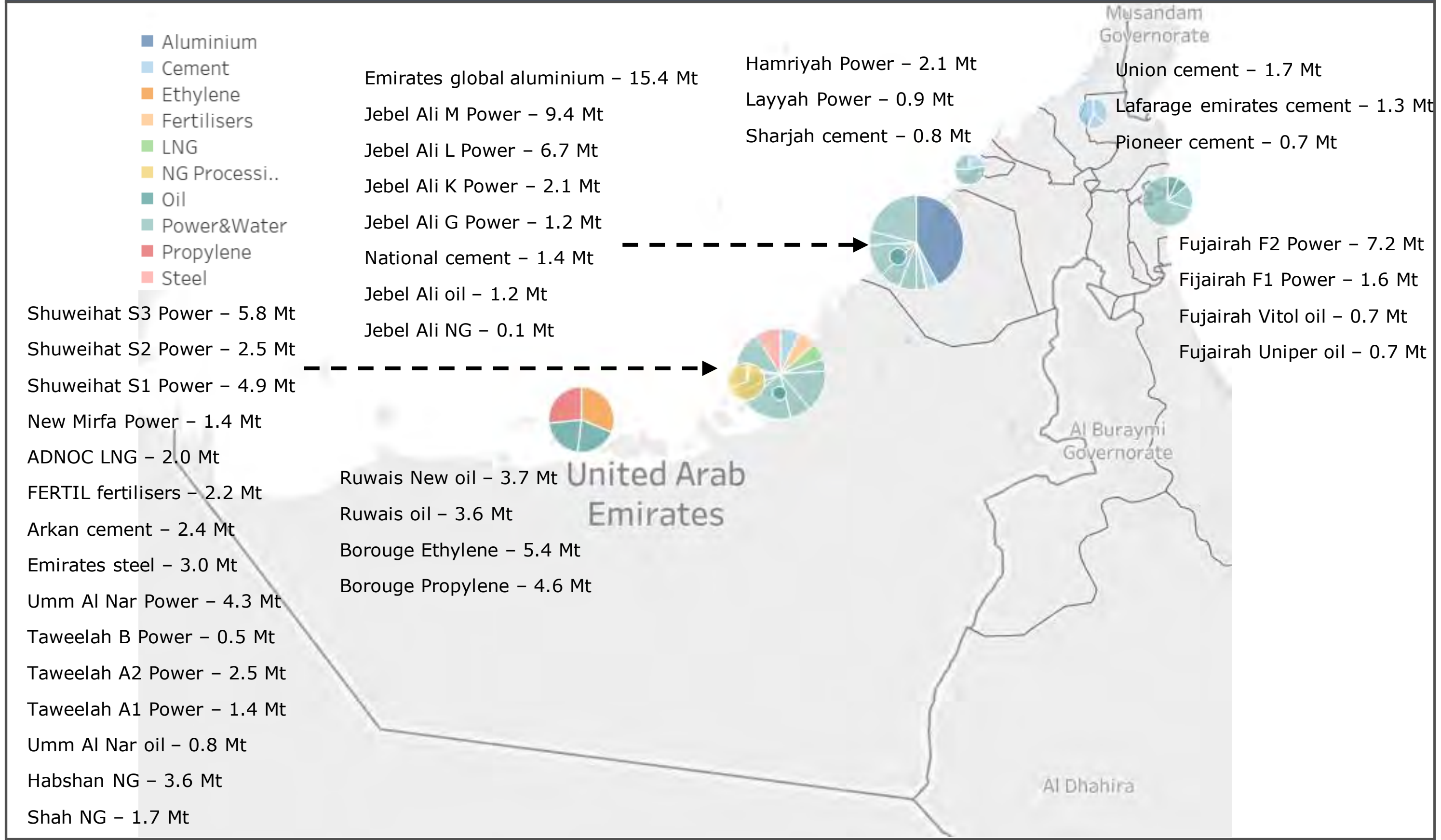
- Cement plants: Southern Province Cement, Yanbu Cement, Al Jouf Cement, Northern Region Cement, Hail Cement, Tabuk Cement, Qassim Cement, Eastern Province Cement, City Cement, Saudi White Cement, Yamama Cement, Saudi Cement, Arabian Cement, United Cement, Al Safwa Cement, Umm Al Qura Cement

Chemical production

- Fertilisers: Ma’aden Phosphate Company, Saudi Arabian Fertiliser Company
- Methanol: Arrazi Saudi Methanol Company, Methanol Chemical Company, Ibn Sina, International Methanol Company
- Ethylene: Petrokemya Company, Sharq Petrochemical Company
- Propylene: Petrokemya Company, Sharq Petrochemical Company

UAE could support two hubs given the clustering of industry and proximity to promising storage reservoirs in the south of the country

UNITED ARAB EMIRATES CO_2 EMISSIONS IN 2019 – 112 Mt



DESCRIPTION

- Abu Dhabi and Dubai are the most industrially active and densely populated emirates in the UAE, and thus, are home to the majority of industrial facilities
- Jebel Ali region in Dubai operates gas-fired power plants and the largest aluminium facility in the UAE, Emirates Global Aluminium (EGA)
- Abu Dhabi has a more diverse range of industries including power, LNG, fertilisers, steel, natural gas processing, petrochemicals and oil refining making it a more attractive CCUS hub than in Dubai
- Abu Dhabi is closer than Dubai to Rub'al-Khali in Saudi Arabia and has significantly higher CO_2 emissions. Emissions from Dubai could be redirected to Abu Dhabi. The UAE is within proximity to the Oman Ophiolite too.

Source: AFRY analysis

CO_2 point sources are clustered on the UAE's west coast in Abu Dhabi and Dubai, with lower significantly lower emissions in other emirates

Electricity generation

- Power Plants: Jebel Ali E, Jebel Ali G, Jebel Ali K, Jebel Ali L-1, Jebel Ali L-2, Jebel Ali M and M extension, Taweelah B, Taweelah B2 extension, New Mirfa, Taweelah A1, Taweelah A2, Shweihat S1, Shweihat S2, Shweihat S3, Umm Al Nar New, Fujairah F1, Fujairah F2, Layah, Hamriyah

Oil & gas activities

- Oil refineries: Fujairah Vitol, Fujairah Uniper, Jebel Ali ENOC, Ruwais ADNOC, Ruwais New ADNOC, Umm Al Nar ADNOC
- Natural gas processing: Bab 1, Habshan, Shah, Jebel Ali
- LNG: ADNOC LNG

Metals production

- Aluminium: Emirates Global Aluminium
- Steel: Emirates Steel Industries

Cement

- Cement plants: Union Cement Company, Lafarage Emirates Cement, Pioneer Cement Industries, Sharjah Cement Company, National Cement Company, Arkan Building Materials

Chemical production

- Fertilisers: Ruwais Fertiliser Industries
- Ethylene: Borouge Abu Dhabi Polymers
- Propylene: Borouge Abu Dhabi Propylene Plant

The formation of CCUS hubs across the GCC region highly depends on the nature of considered industries and their proximity to natural carbon sinks

Nature of the considered industries

- GCC industrial facilities produce flue streams with variable CO_2 concentrations depending on the nature of the industry and the involved processes
- Industrial facilities have numerous point CO_2 sources making their complete decarbonisation challenging. However, capturing CO_2 from flue streams of specific processes is technically and economically possible
- Capturing CO_2 is easier and more feasible for industries and processes that produce high purity CO_2 flue streams. These streams result from the ease of separation of CO_2 and other impurities in flue streams.

Proximity to natural carbon sinks

- The GCC region is technically competitive with other regions with respect to storage presence, quality, and volumes
- Carbon could potentially be stored in depleted gas reservoirs and saline aquifers
- The GCC region has significant opportunity across 11 sedimentary sequences and the Oman ophiolite. Moreover, member states could utilise depleted gas reservoirs for carbon storage especially Saudi Arabia and the UAE.
- Carbon storage density is highest in the Rub'al Khali basin and Kuwait

Capturing CO_2 is more feasible for industries that produce high purity CO_2 flue streams

Increasing CO_2 concentration in flue streams

Variable concentration 2 – 65%	Extremely dilute 0.04-1%	Very dilute 3-8%	Dilute 10-25%	High purity 40-100%
Natural gas processing	• Ambient air – 0.04-0.06%	• Gas turbines – 4-6% • Industrial furnaces – 8% • LNG • Aluminium	• Cement – 22.5% • Refinery crackers – 10-18% • Steel & Iron	• Petrochemicals – 100% • Fertilisers – 97% • Methanol – 99% • Hydrogen – 45%

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Proximity to natural carbon sinks and their storage capacities are other deterministic factors for the formation of CCUS clusters

Depleted gas reservoirs

- Saudi Arabia and the UAE have substantial potential for CCS in depleted gas fields with best estimates of 5.2 Gt and 5.9 Gt, respectively*
- Due to the Saudi reliance on associated gas, the depletion of non-associated gas fields is expected to be relatively slow. On the other hand, the UAE has a large number of gas fields with a good mix of mature and immature fields that could provide for shorter term start up and phased CCS projects as gas fields become available
- Estimates of storable quantities for the GCC region are dominated by Qatar because of the massive storage capacity of the North Field. Nevertheless, at current production rates the North Field is likely to remain productive for hundreds of years and hence it can't be considered part of the regional CCS solution
- Estimates of storable quantities in Oman, Bahrain and Kuwait are 1 Gt or less.

Saline aquifers and geological storage

- Carbon storage density is highest in the Rub'al Khali basin and Kuwait with the low to high estimates ranging from 36 $GtCO_2$ to 318 $GtCO_2$ (best estimate of 118.5 $GtCO_2$)
- Rub'al Khali makes Saudi Arabia an excellent candidate for CCUS hubs due its massive CO_2 storage capacity. Large CO_2 emissions in Qatar and the UAE also makes them favourites to utilise storage capabilities in Rub'al Khali
- No significant potential for geological storage is seen in the Red Sea Basins which implies that CO_2 captured on the west coast of Saudi Arabia has to be transported to Jubail
- Oman Ophiolite has a tentative storage potential of 8.2 $GtCO_2$

*Estimated in Chapter 3 on Carbon sinks

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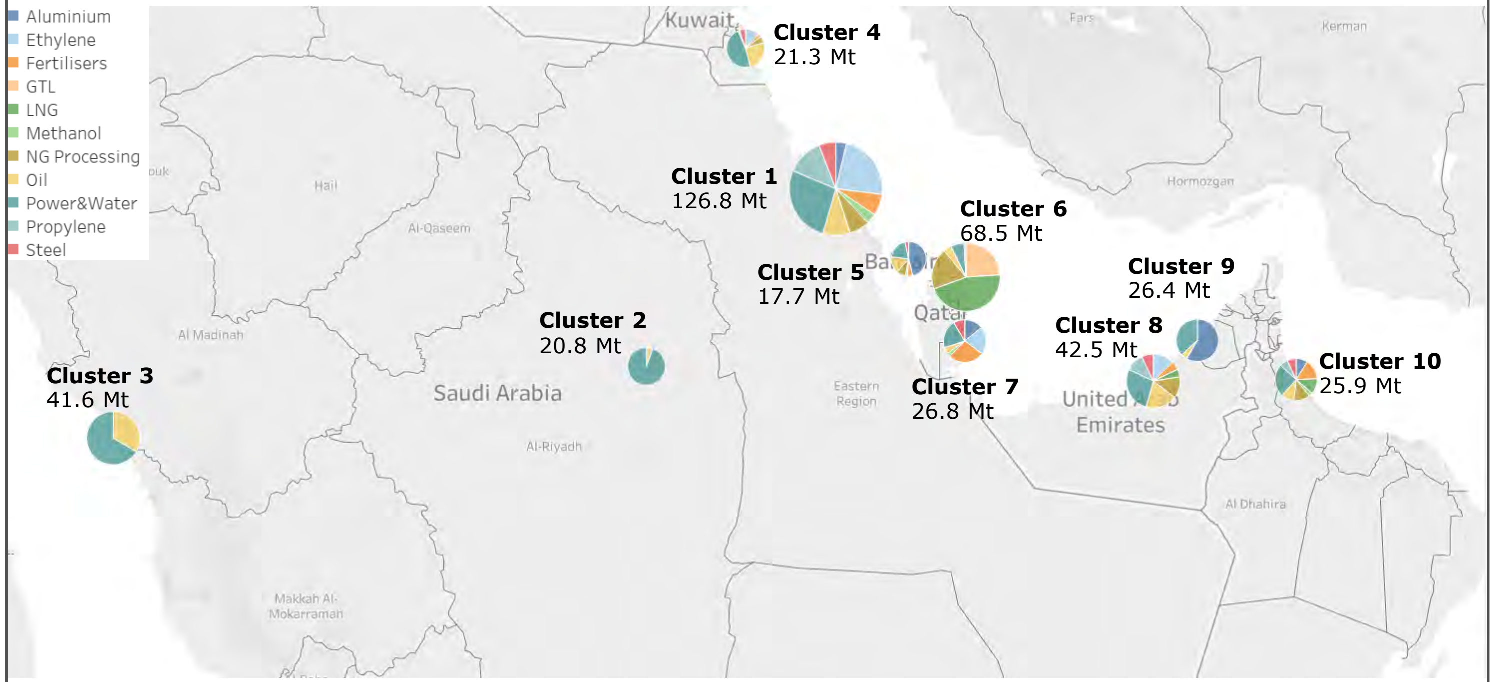
Substantial CO_2 emissions and proximity to sinks make Saudi Arabia, Qatar, and the UAE favourable for commercial-scale CCUS hub development

POTENTIAL GCC CLUSTERS CO_2 EMISSIONS IN 2019 – (Mt)



DESCRIPTION

– CO_2 emissions on the east coast of Saudi Arabia stem from a diverse range of industries many of which are relatively easy and cheap to capture making Jubail the largest and most promising CCUS hub in the GCC region

– Yanbu CO_2 emissions are high but predominantly originate from the power sector making them more complex and expensive to capture

– The active LNG, GTL, and natural gas processing sectors make northern Qatar the second favourite CCUS hub after Jubail. The southern region of Qatar also has cheap capture cost industries like petrochemicals and fertilisers but with lower overall CO_2 emissions

– The majority of Kuwait's emissions are derived from the power and oil refining sectors leaving less than 5 $MtCO_2$ across easy to capture sectors. However, due to its proximity to Jubail and its storage potential, it could be combined with Jubail

– The bulk of Bahrain's emissions emanate from the aluminium sector and the country's capturable emissions could be combined with those of Qatar

– Abu Dhabi seems more favourable as a CCUS hub in the UAE due to petrochemical, fertilisers, and natural gas processing activities in Ruwais. The emirate plans to introduce its first methanol facility in 2025 adding to the capacity of easy carbon capture industries. Emissions in Dubai are dominated by the power and aluminium sectors which poses more challenges for the development of a standalone hub

– Although Muscat Governorate and its vicinity have comparable CO_2 emissions as in Dubai, the diversity of industries and the contribution of low capture cost industries to the emissions make northern Oman a potential CCUS hub which could also be combined with Abu Dhabi's hub

Source: AFRY analysis

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Jubail, Northern Qatar and Abu Dhabi have the highest share of high purity CO_2 emissions

#	Hub	Very dilute 3-8%	Dilute 10-25%	High purity 40-100%	Close geological sinks
1	Saudi Arabia - Jubail	38.7 Mt	7.4 Mt	80.7 Mt	Rub'al Khali
2	Saudi Arabia - Riyadh	19.7 Mt	-	1.1 Mt	Rub'al Khali
3	Saudi Arabia - Yanbu	27.6 Mt	-	14.0 Mt	Rub'al Khali/Red Sea
4	Kuwait	10.1 Mt	1.1 Mt	10.1 Mt	Rub'al Khali if connected to Jubail
5	Bahrain	11.7 Mt	0.6 Mt	5.4 Mt	Rub'al Khali if connected to Jubail
6	Qatar - North	35.4 Mt	-	33.1 Mt	Rub'al Khali if connected to Jubail
7	Qatar - South	9.5 Mt	2.3 Mt	15.0 Mt	Rub'al Khali if connected to Jubail
8	UAE – Abu Dhabi	13.8 Mt	3.0 Mt	25.7 Mt	Rub'al Khali/Oman Ophiolite
9	UAE – Dubai	25.1 Mt	-	1.3 Mt	Rub'al Khali/Oman Ophiolite
10	Oman	11.9 Mt	1.8 Mt	12.2 Mt	Rub'al Khali/Oman Ophiolite

* The figures represent total emissions by sector and not capturable emissions

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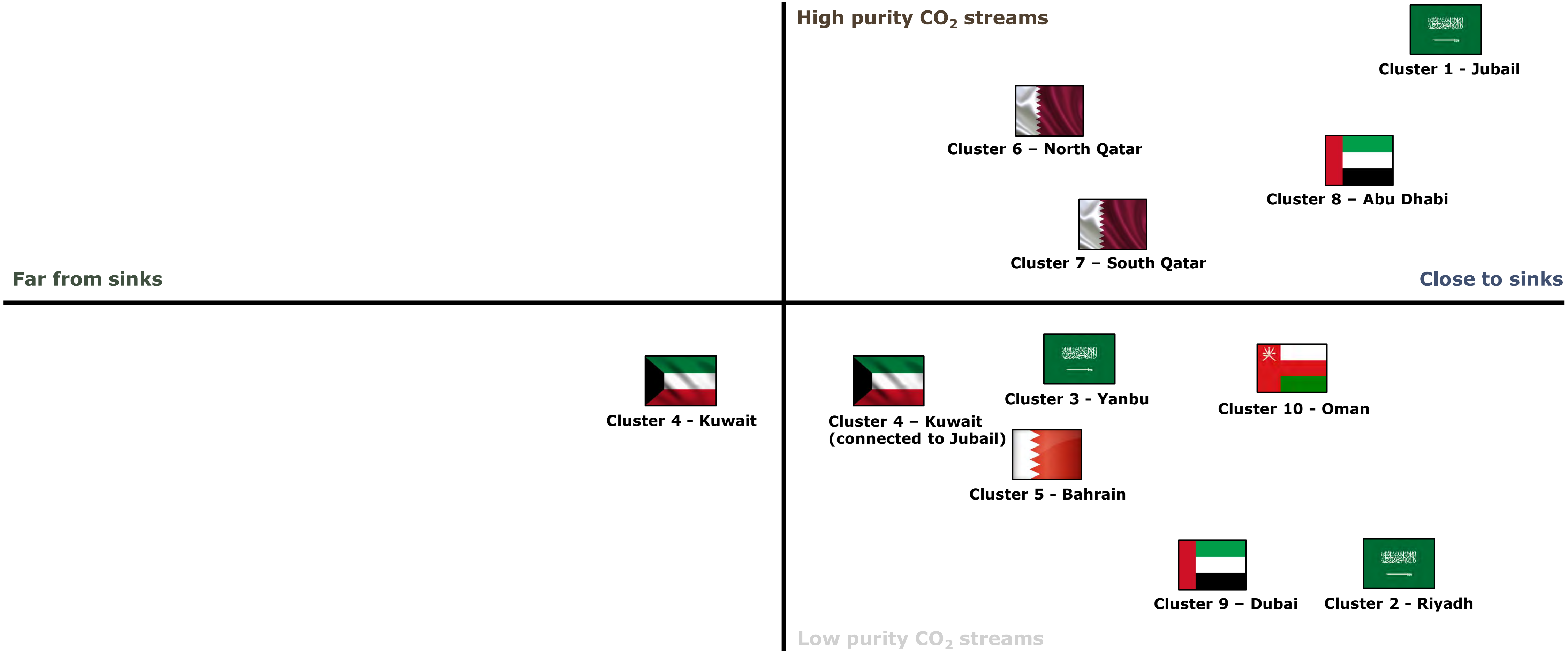
The most promising clusters have substantial high purity CO_2 emissions and are close to geological sinks



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CHAPTER 5

Macroeconomic Analysis

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The development of CCUS and Hydrogen will open up new market opportunities and protect income and employment in key industrial sectors

NEW MARKET OPPORTUNITIES

- We estimate new market opportunities in hydrogen export and CO_2 storage services could add **US$15.5bn** to **44bn** in gross value added (GVA) to the GCC in 2050 and support between **87,300** and **245,400** jobs (directly and in the wider economy)
  - As global hydrogen demand increases in response to pressures for decarbonisation, the GCC is well placed to establish itself as a key producer and exporter of low-carbon hydrogen with a potential global market share of between **16% and 19% by 2050**
  - The export revenues associated with this new export market would be between **US$50bn and 140bn** in 2050 contributing **US$15bn – 42bn in value added** and supporting **86,000 to 242,000 jobs**
  - The CO_2 storage hub developments will provide an opportunity to offer storage services for imported CO_2. in 2050, if 50 Mt/yr of imported CO_2 is stored, revenues may be in the range of **US$500m to 2bn** in 2050, contributing **US$300m to 1.2bn** in value added and supporting **1,300 to 3,400 jobs** across the economy

EXISTING INDUSTRIES AND CCUS INVESTMENT

- Domestic CCUS deployment would see around **US$180bn of investment** in capture, transport and storage infrastructure by 2050.
- The manufacture, construction, operation and maintenance of this CCUS infrastructure would directly support around **30,000 jobs**
- Without deployment of CCUS and Hydrogen, economic activity in the main industrial sectors would be unsustainable. By investing in CCUS and hydrogen, the GCC will **protect employment and income** in those sectors.
- Effective decarbonisation of industrial activity also enables the GCC to maximise its future oil and gas production

Source: AFRY analysis, Scottish Government, Supply, Use and Input-Output Tables (published Nov 2021); and UK Office for National Statistics, Supply and Use Tables

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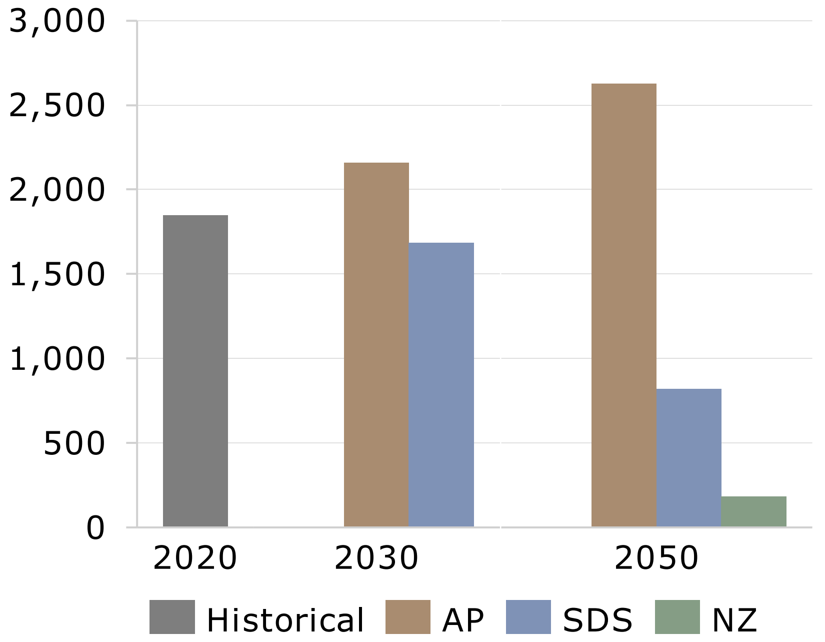
Under various scenarios for decarbonisation, emissions across the Middle East will need to fall by between 56% and 90% by 2050

SCALE OF THE CHALLENGE

- Without any mitigation action beyond that already committed by national governments, the IEA projects that emissions across the Middle East would rise by 42% from 2020 levels by 2050 (source: IEA WEO 2021, Announced Pledges scenario).
- The IEA projections do not account for more recent announcements to deliver net-zero by 2050 or 2060 made by UAE, Bahrain and Saudi Arabia respectively
- Published decarbonisation scenarios in line with these new pledges require a decrease of between 56% and 90% over 2020 levels by 2050 to put the region on a trajectory towards delivering net-zero by 2060
  - The lower figure corresponds to the 2021 WEO Sustainable Development scenario
  - The higher figure is assumed based on a goal of achieving net zero by 2060
- The majority of this reduction is anticipated post-2030
- In a net-zero scenario global oil demand is projected to fall from 91mb/d to 24mb/d, with OPEC market share in 2050 being 52%

GCC EMISSION TRAJECTORIES UNDER ALTERNATIVE IEA SCENARIOS (MT CO_2)



* no NZE figure for 2030 in the published scenarios (total emissions are available but there are no regional figures available)

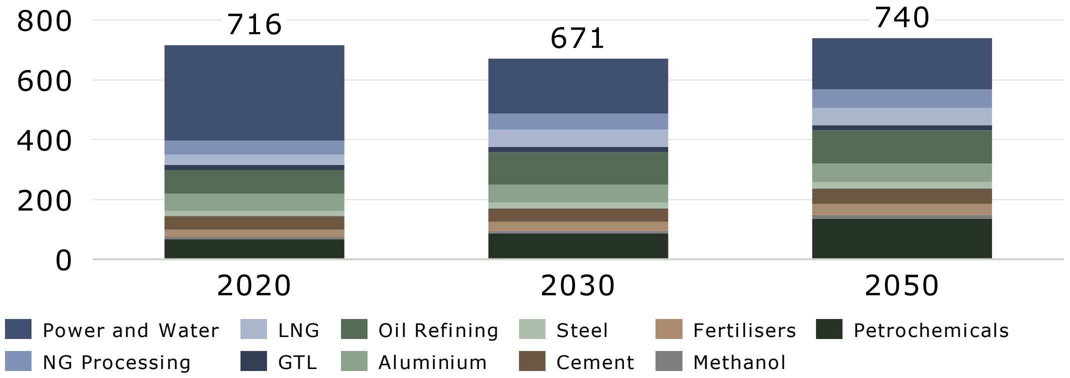
Source: IEA WEO 2021

Our analysis of Carbon Sources shows that industrial activity levels are incompatible with necessary decarbonisation trajectories without mitigation

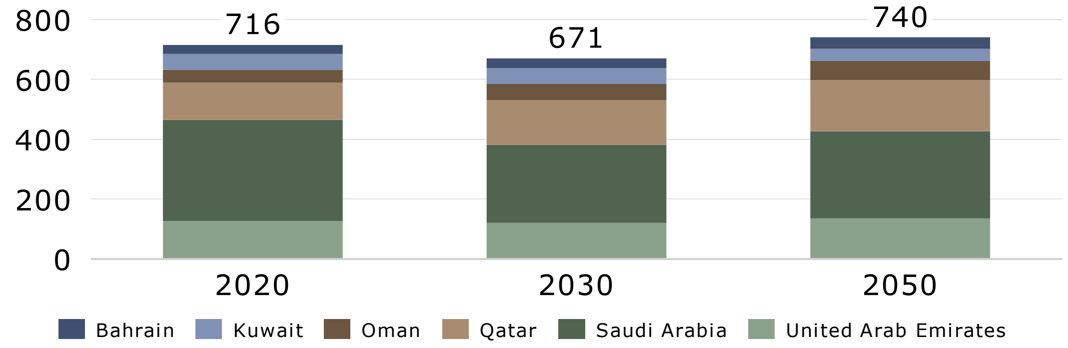
COMMENTARY

- Assuming current output emission intensities for key sectors, total industrial emissions would be 3% higher in 2050 than where they were in 2020 (716 to 740MtCO_2/yr)
  - Power and water sector emissions are expected to fall by 46%, reflecting the switch from oil to gas and renewables
  - All remaining sectors see increases in emissions driven by income and population growth assumptions
  - Petrochemicals are expected to more than double their emissions
- These activity levels will only be realised if there is investment in carbon capture technology or other low-carbon solutions
- **The application of CCUS and/or the use of low-carbon hydrogen in production processes is needed to protect the jobs and output in these key sectors**

EMISSIONS BY INDUSTRIAL SECTOR IN THE GCC, MTCO_2/Y*



EMISSIONS BY COUNTRY IN THE GCC, MTCO_2/Y*



* 2020 corresponds to historical data; 2030 and 2050 are projections; AFRY analysis (Chapter 2 – Carbon Sources)

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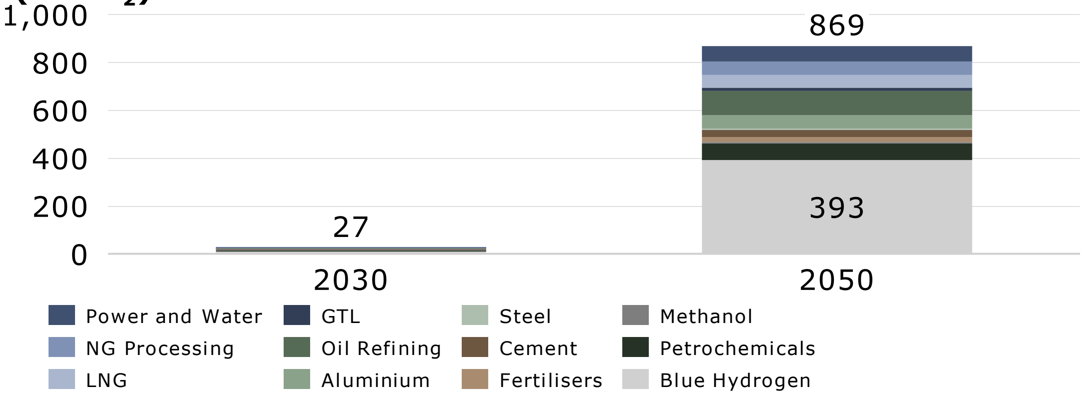
Our initial expectation is that decarbonisation of key industry sectors will ramp up slowly until 2030 but accelerate thereafter

COMMENTARY

- In 2030, 27 $MtCO_2$ will be captured. This corresponds to around 4% of projected industrial activity (excluding blue hydrogen production)
  - This is around half the level of emission reduction implied in the IEA's Sustainable Development scenario, highlighting the challenge of delivering these ambitious transformations
- In 2050, we assume capture levels are in line with the IEA Sustainable Development scenario
  - 869 $MtCO_2$ will be captured, of which 476 Mt, 65% of projected activity levels, is from the main industrial sectors. The remainder is captured from blue hydrogen production.
- The proportion of activity supported through carbon capture varies significantly across sectors. Our assumptions for this are based on average global capture rates for each sector, and map well to the sectors with high potential from earlier workstreams.

EMISSIONS CAPTURED BY INDUSTRIAL SECTOR IN THE GCC ($MTCO_2$)



Sector	Share of Emissions Captured in 2050
Blue Hydrogen	100%
NG Processing, LNG, GTL, Oil Refining, Aluminium	90%
Cement	61%
Fertilisers, Methanol, Petrochemicals	51%
Power	38%
Steel	28%

AFRY approach to estimating macroeconomic impacts of CCUS in key industries in the GCC considers three classes of jobs and economic value

REPRESENTATION OF MACRO-ECONOMIC ANALYSIS APPROACH

1 Direct employment in CCUS industry – Capture – T&S	– Based on IEA SDS industrial growth in CCUS and hydrogen, and AFRY / Gaffney Cline cost analysis – Quantified estimates based on recent public studies per $m/annum of CCUS investment including jobs for installation, operation and in supply chains
2 Direct jobs associated with exports (+ GVA) – H2 export – CO_2 imports	– Estimates of jobs created and GVA value creation from export industries – Quantified estimates using total export size and input/output tables
3 Protected jobs and retained economic value in major industries – Metals – Chemicals – Oil and gas – Cement	– Qualitative approach only – Clear argument that CCUS development is key to retaining industries in a low-carbon transition

COMMENTS

- Overall we assess two main categories of CCUS impacts on GCC jobs:
  1. Quantitative employment estimates:
     a) in the CCUS sector (capture and T&S) and
     b) additional employment in key export sectors
  2. Qualitative description of additional ‘protected jobs’ in industries that are exposed in low-carbon transition
     - Metals, chemicals and cement are relatively high carbon sectors with significant domestic and potential export markets;
     - Oil and gas sector where CCUS globally is key to keeping fossil fuels in the overall global economy
- Based on IEA Sustainable Development Scenario data as far as is possible to represent the overall size of the market in 2050. Key data points include:
  - Overall size of the global hydrogen market, and proportion delivered by GCC
  - GCC CO_2 captured
  - Global gas and oil demand (including Net Zero scenario and comparison as a more restricted benchmark)
- Consistency with hydrogen market analysis and cost evolution analysis elsewhere in the study

Element Energy/Vivid Economics (2019), CCUS in Saudi Arabia: The Value and Opportunity for Deployment; AFRY/Cambridge Econometrics (2021) Economic Analysis of UK CCUS, a Report to the CCSA; and Vivid Economics (2019) Energy Innovation Needs Assessment (CCUS), for BEIS

Capital investment to deliver the CCUS and hydrogen infrastructure may reach $180bn by 2050 and support up to 30,000 direct jobs

COMMENTARY

- Domestic CCUS deployment will require investment of around **US$180bn** by 2050
  - Almost half of the capture spend is attributable to hydrogen production to support the large export market potential
  - A $60bn carbon transport and storage infrastructure investment will underpin the use of capture technologies across the main industrial sectors
- The CCUS sector itself can support up to **30,000 jobs** in the manufacture, installation and operation of capture, transport and storage infrastructure.
  - This estimate is derived from :
    - a 1000 Mt/yr CO_2 capture volume
    - An assumption of 30 direct jobs per $MtCO_2$ captured, taken from previous work by Element Energy/Vivid Economics

INVESTMENT PER YEAR & CUMULATIVE

Cumulative capex spend	$m by 2030	$m by 2050
Natural Gas Power	83.2	6622.1
Refinery	844.3	29342.7
Iron and Steel	313.5	12179.1
Cement	379.9	4348.4
Hydrogen	2226.1	54954.1
Chemicals	413.3	3848.4
Natural gas processing	186.2	6980.6
Fertiliser	126.3	982.8
Total capture spend ($m cumulative)	4,573	119,258
Total T&S spend ($m cumulative)	3,160	63,663

Element Energy/Vivid Economics (2019), CCUS in Saudi Arabia: The Value and Opportunity for Deployment

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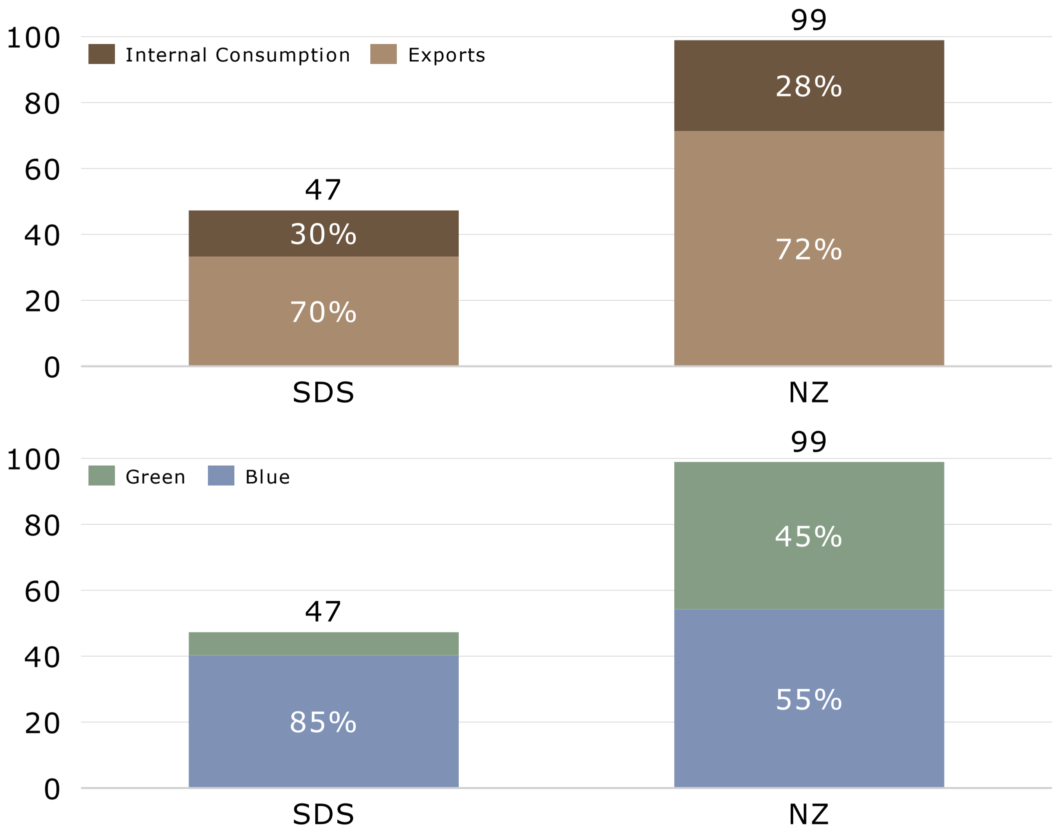
Hydrogen production is projected to grow in response to both industry needs and export opportunities

COMMENTARY

- Hydrogen use within the GCC will grow to between 14 and 27 Mt/yr by 2050, depending on the speed of decarbonisation
  - The majority of domestic hydrogen demand will be for the transport sector, accounting for more than half of the consumption
- Global hydrogen demand by 2050 is anticipated to be in the range of 269 to 520 Mt/yr and we assume that the GCC will be a major exporter with a market share of the global hydrogen production in the 16% to 19% range by 2050
- Global hydrogen prices, net of transport costs, are projected to be in a range from 1.5 to 2$/kgH2 (in 2030) capped at green hydrogen production costs in the export market
  - At these prices, 2050 export revenues may be between **50$bn** and **140$bn** (revenue net of transport costs)
- The balance of blue and green hydrogen will vary depending on the scale of decarbonisation
  - 85% of the hydrogen produced in the GCC will be blue by 2050 in the Sustainable Development scenario
  - For the Net Zero scenario a large proportion of the additional volume will be green hydrogen

HYDROGEN PRODUCTION BREAKDOWN BY 2050, MT/Y



The hydrogen export activities may add 15 – 42 US$bn GVA to the GCC region and support 86,000 to 242,000 jobs

OVERVIEW OF METHODOLOGY

- Employment and Gross Value Added (GVA) estimates have been derived by applying economic multipliers to the estimated value of hydrogen exports (net of transport costs) in 2050
- The 'economic effect' multipliers show the full time equivalent jobs (FTEs) or GVA for each $m of output from the activity.
- Type I multipliers refer to the impacts on the direct and indirect (i.e. supply chain) sectors, whereas Type II multipliers also include induced impacts on wider economic activity.
- We have used employment and GVA effect multipliers from the UK to estimate the impact of the estimated hydrogen export market revenue (output) in 2050
  - The latest economic multiplier data (for 2018) are produced by the Scottish government and are in line with those produced by the UK ONS (latest data 2015)
  - For employment effects we have deflated the 2050 output values to their 2018 value using an assumed 2% annual inflation adjustment
- We have assumed hydrogen production uses multipliers for the Petrochemicals sector.

ASSUMED MULTIPLIERS

	Type I	Type II
Employment effect	2.5	3.3
GVA effect	0.3	0.4

- For example, using these proxy multipliers US$1bn of export revenues would
  - provide an additional $300m of GVA to the direct and indirect sectors and a further $100m GVA in the wider economy
  - support 2,500 jobs in the direct sector and related supply chain and an additional 800 jobs in the wider economy

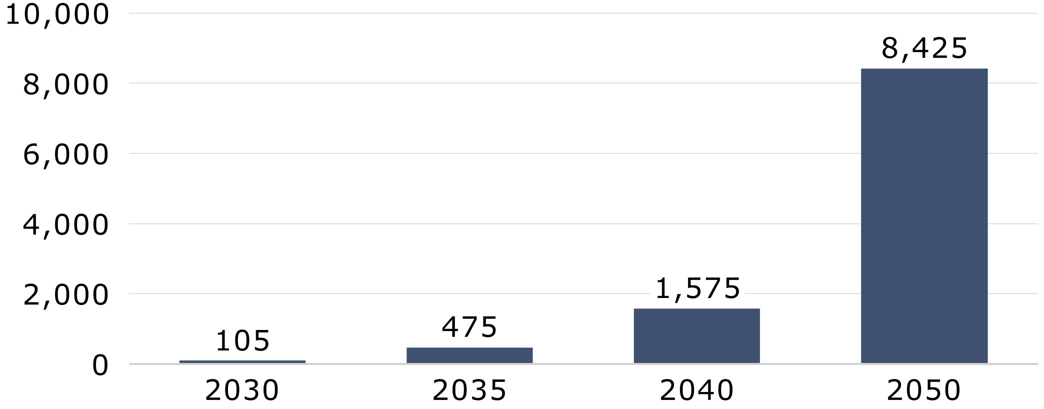
Scottish Government, Supply, Use and Input-Output Tables (published Nov 2021); and UK Office for National Statistics, Supply and Use Tables

CO_2 storage requirements will grow over time and storage potential in the region is well beyond projected requirements

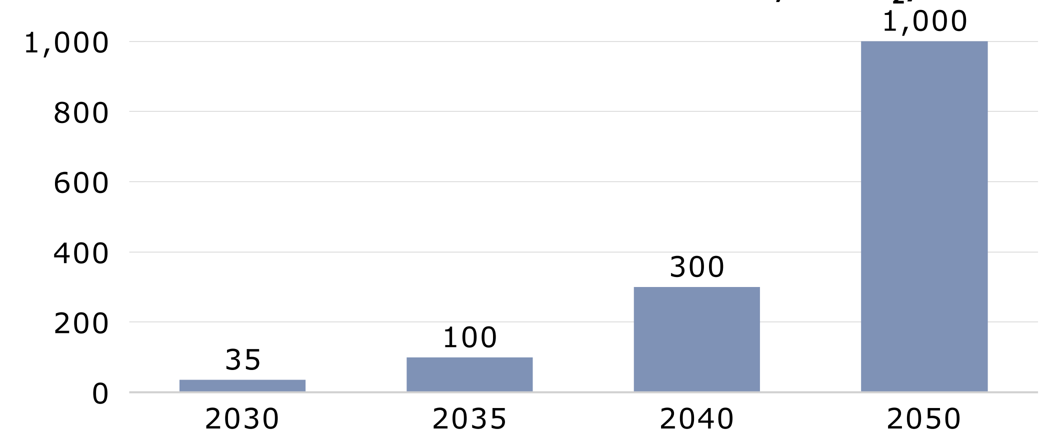
COMMENTARY

- All sustainable scenarios see a rapid increase in annual capture volumes over time
  - By 2030 **35 $MtCO_2$/y** are captured, below the IEA's SDS projection of 100 $MtCO_2$/y in 2030 and the current announced figure of 44$MtCO_2$/yr in Saudi Arabia Alone (Calculations only consider 2050 position though)
  - For 2050 our projections are in line with the SDS, reaching 1,000 $MtCO_2$/y, though based on a comparison of IEA scenarios, annual capture rates to achieve net zero would need to be around 1400 $MtCO_2$/y
- Cumulative CO_2 capture by 2050 will be in the region of **8.4 $GtCO_2$**, which is less than 10% of the identified storage potential
- Development of three storage hubs by 2030 would provide access to **120 - 140 Mt** of storage capacity with further
- There is limited evidence of a role for CO_2 import services in the literature and scenarios reviewed
  - We propose to consider two scenarios for import services – **no import services** and a scenario where import services are **5% of total domestic capture** requirements

CUMULATIVE CARBON CAPTURE IN THE MIDDLE EAST, $MTCO_2$



ANNUAL CARBON CAPTURE IN THE MIDDLE EAST, $MTCO_2$/Y



Source: Scottish Government, Supply, Use and Input-Output Tables (published Nov 2021); and UK Office for National Statistics, Supply and Use Tables

If viable, CO_2 import storage services may add 0.3 – 1.2 US$bn of GVA to the GCC region and support 1,300 – 3,400 jobs across the economy

OVERVIEW OF METHODOLOGY

- Employment and Gross Value Added (GVA) estimates have been derived by applying economic multipliers to the estimated output (revenue) from CO_2 storage in 2050 (based on 50 $MtCO_2$ storage demand from imports)
- The 'economic effect' multipliers show the FTEs or GVA for each $m of output from the activity.
- Type I multiplier refer to the impacts on the direct and indirect (i.e. supply chain) sectors, whereas Type II multipliers also include induced impacts on wider economic activity.
- We have used employment and GVA effect multipliers from the Scottish government (latest data 2018)
- We have assumed CO_2 storage uses multipliers for the 'Manufacture and distribution of gas through mains'.
- Total potential revenue in 2050 is estimated at **US$500m – 2000m**, based on a storage cost of **10 - 40$/$tCO_2$**

ASSUMED MULTIPLIERS

	Type I	Type II
Employment effect	4.1	5.0
GVA effect	0.5	0.6

- For example, using the proxy multipliers assumed, US$1bn of export revenues would:
  - provide US$500m of GVA to the direct and indirect sectors and a further US$100m of GVA to wider activities
  - support 4,100 jobs in CO_2 storage activities and associated supply chain and a further 900 jobs in the wider economy

Scottish Government, Supply, Use and Input-Output Tables (published Nov 2021); and UK Office for National Statistics, Supply and Use Tables

CHAPTER 6

Business Models

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CCUS business models need to be appropriate to incentivise the full chain of capture, transport and storage while allowing for shared infrastructure

INTRODUCTION TO CCUS BUSINESS MODELS

– CCUS involves multiple competencies and skillsets covering capture, transport and storage of CO_2 which typically involve multiple parties working together to deliver the full chain.

– In addition the main driver for the widespread adoption of CCUS – reducing CO_2 emissions – frequently carries insufficient (or no) economic incentive, meaning that it also typically involves additional government intervention.

– Getting the ownership, revenue streams and incentive structures right can help CCS to develop successfully, and potentially opens up economies of scale from sharing common infrastructure between different capture projects. Unsuitable business models can increase costs and result in less or no CCS development.

– For the purposes of this report we define the business model for CCUS as a description of:

  – allocation of roles and responsibilities across the main areas of the CCUS chain; and

  – allocation of risks and incentives

  – outline of the commercial incentives and payment flows

REPORT SECTION STRUCTURE

– In this section we focus on CCUS within the Gulf Cooperation Council states and look at:

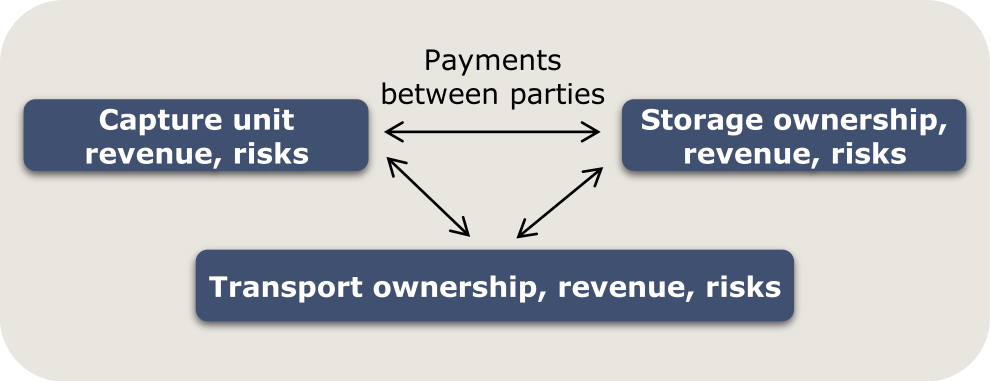
  - the main barriers and market failures for CCUS;

  - key options for a business model;

  - our assessment of these options; and

  - our recommendation for how to put a business model together.

– Our focus on the business models is split into first considering carbon capture, and then business models for CO_2 transport and storage. While any CCS system needs to integrate these parts, the distinct nature of the activities involved means there is value in considering each component individually.



On a global level, common deployment risks, barriers and market failures for CCUS have caused many proposed CCUS projects to fail in recent decades

GENERAL RISKS AND BARRIERS TO EARLY STAGE INDUSTRIES

Technology, construction and performance risks
Principally applies to capture and storage, and drives higher costs of capital and required contingencies

Capital market restrictions
Limited availability of equity and debt finance for CCS. Significantly less of an issue than it used to be and not major barrier for GCC if the risk allocation is acceptable

Policy instability risk
Causes developers to shorten investment horizons and unwilling to finance follow up or more speculative projects. Risks in GCC likely to be substantially less than other world regions

Public perception risk
Lack of public knowledge and acceptance can create significant delays to obtaining licences, consents, and local approval. Risks in GCC likely to be substantially less than other world regions

SPECIFIC BARRIERS AND MARKET FAILURES FOR CCUS

Emission externalities
CO_2 price faced does not reflect damage to other parties, leaving insufficient economic incentive to reduce emissions.

Coordination failures
Firms depend on other firms to successfully operate, leaving cross-chain and volume risks.

Imperfect or asymmetric information
Insufficient or confidentially held information (e.g. storage geology) does not allow effective competition.

Knowledge creation
Firms can be reluctant to take the first step – particularly where they could instead wait and learn from the actions of other firms

Natural monopoly industries
Transport and storage will have significant localised market power. No real competition for auctioning network expansions.

Missing markets
No established markets for CO_2 transport/storage makes financing of elements hard so only integrated projects develop.

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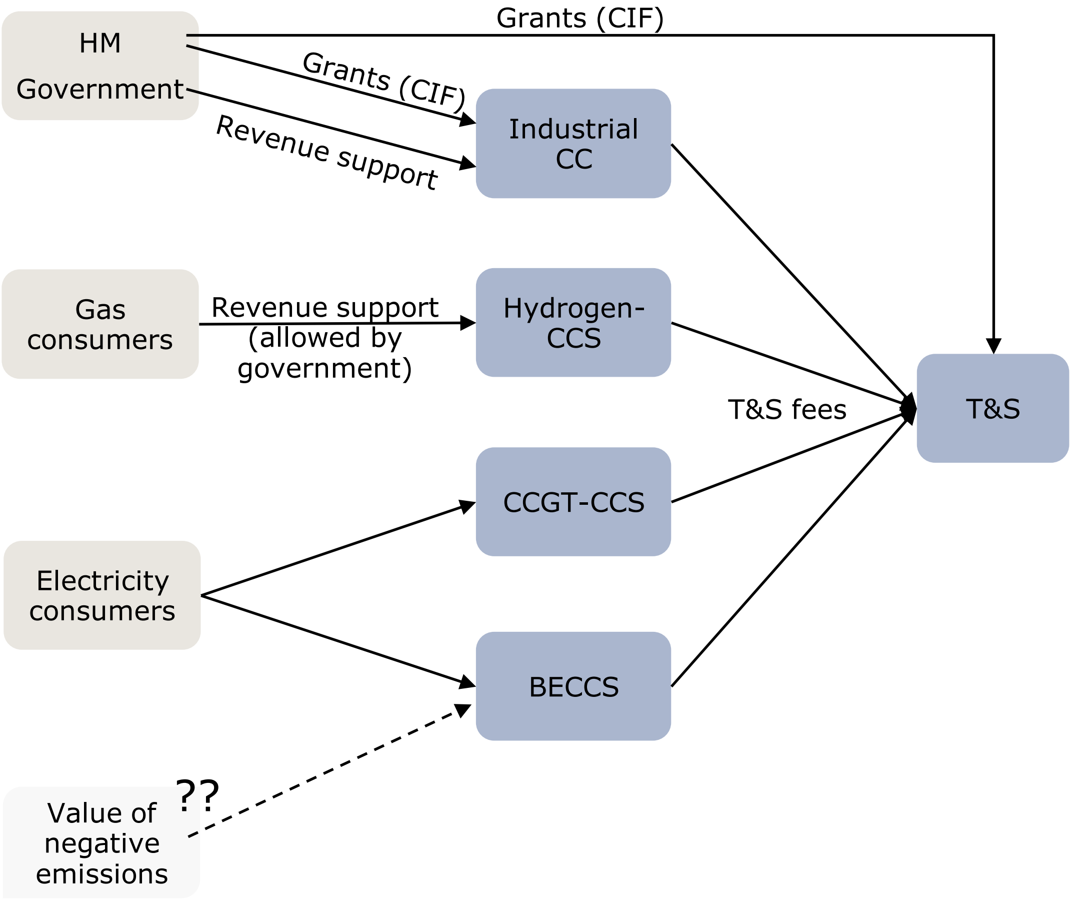
The UK business model varies by contracting approach across the 5 sectors of Industry, Hydrogen, Power, BECCS and T&S

BUSINESS CASE IN THE UK

- Capture parties receive revenue support in the form of:
  - **Grants**, such as the Capital Infrastructure Fund (for Industry)
  - Competitively allocated **revenue support** based on agreed contract terms with the government which vary by industry:
    - gas consumer annual payments for (blue) H_2 provided
    - electricity consumer annual payments for CCS power plants or bioenergy with carbon capture and storage (BECCS)
  - New forms of revenue may appear such as rewarding negative emissions at carbon market price
- Additional costs include capex and opex for CCS equipment, however, sites also benefit from lower costs for purchasing carbon allowances for any residual emissions
  - Payments are therefore structured around a CfD structure (where subsidy is reduced when market price increase)
- Concept is that the subsidy payment allows for a return on the CCS investment and pass-through of T&S fees, but otherwise only covers the costs of running capture part not other operational site costs
- Transport & Storage is conducted by a separate T&Sco, with partial Grant funding. It is then expected to be funded via a regulated T&S fees from the capture projects (which are allowed to pass-through the costs)

OVERVIEW UK FUNDING MODEL



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Contracts for UK CCS hubs are allocated via a Phase / Track process, although contract details are still being finalised during the bidding window

UK GOV CCUS DEPLOYMENT STRATEGY

- The UK Government's *Ten point plan* and *Net Zero Strategy* set out ambition to deploy CCUS at scale in the UK, targeting:
  - two industrial clusters by the mid-2020s, + further two by 2030, aka 'SuperPlaces', capturing 20-30 MtCO_2 per year by 2030
- **Cluster Sequencing Process**
  - **Phase-1** identified and sequenced CCUS clusters suited to deployment in the mid-2020s ('Track-1'), announced Oct 2021:
    - Selected successful clusters: ***Hynet*** (North West and North Wales) and ***East Coast*** (Teesside and the Humber) Cluster
    - *Scottish Cluster* (based at St Fergus, NE Scotland) announced as a reserve cluster
  - **Phase-2 –** launched Nov 2021 - opened to application from Power, Industrial Carbon Capture and Hydrogen production projects.
  - At the end of 2022 progress will be reviewed to consider further actions required post mid-2020s

2020	– 2020-2025: Build CCUS network infrastructure in the first two clusters, i.e. 'Track-1'
2025	– 2025-2030: CCUS infrastructure expanded to additional clusters, i.e. 'Track-2'
2030	– 2020-2030: Demonstration of CO_2 capture across a range of industries
…	
2045	– 2028-2045: CCUS networks expanded to remaining clusters and beyond, exporting technical development

MAJOR UK INDUSTRY CLUSTER EMISSIONS

- Large emission clusters indicate likely applicants for Phase-2, however this map is not exhaustive
- It is a complex process to get stakeholders in a hub to both work together yet bid separately for contracts

Sources: Industrial decarbonisation strategy, BEIS, 7 April 2021. Cluster sequencing for carbon capture, usage and storage (CCUS) deployment: Phase-2, BEIS, 8 Nov 2021. Net Zero Strategy: Build Back Greener, BEIS, 19 Oct 2021. Map - NAEI 2018 data reported by BEIS 2021

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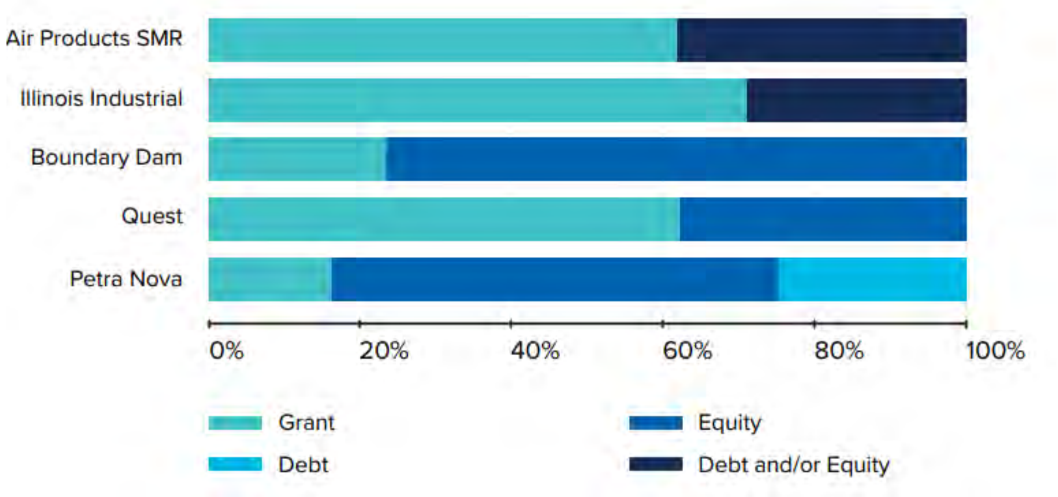
While there is no clear-cut business model in the US, the majority of projects to-date have leveraged EOR synergies and government support

BUSINESS CASE IN THE US

- While there is no clear-cut business model for CCUS, successful US projects have relied on a set of primary economic drivers:
  - **Enhanced oil recovery** has been the main way through which value is placed on capturing CO_2. For example, the cost of CO_2 is around \$30/tCO_2 with oil prices of \$70/bbl.
    - The revenue from the sale of CO_2 for EOR alone may be sufficient to cover the costs of capturing and transporting CO_2 in natural gas processing, fertiliser and bioethanol production where the cost of capturing CO_2 is relatively low.
    - This combination of favourable project costs and revenues from the sale of CO_2 for EOR was the main driver of early CCS projects in the US, such as Terrell, Enid and Great Plains.
  - In cases where project economics cannot be entirely supported through EOR, **government support** in the form of incentives and grant funding has been instrumental in expanding the applications and industries where CCS is economically viable.
    - **45Q tax credit** provides \$35/t for use of CO_2 in commercial applications and \$50/t for permanently sequestering captured CO_2.
    - **Grant funding** from the Department of Energy (DOE) makes up a considerable portion of capex costs for emerging capture and storage technologies that would have otherwise been borne by the developer. For example, grants accounted for more than 60% of capex costs for the Air Products SMR and Illinois Industrial projects.
  - A number of states in the US impose carbon prices on emissions from large power and industrial sites, to date this has not been a driver for the uptake of CCUS

PROPORTION OF GRANT FUNDING PROVIDED TO SELECTED CCS PROJECTS IN NORTH AMERICA[1]



[1] Global CCS Institute, Policy Priorities to Incentivise Large-Scale Deployment of CCS, April 2019

GCC has particular barriers to CCUS development which a successful business model will need to overcome, but also competitive advantages

KEY CHALLENGES

1. *No primary financial incentive (carbon price) for CCUS*
   - Drivers currently weaker than regions such as Europe, Canada and China and insufficient to incentivise CCUS
   - Additional government support will likely be needed, and will likely need to continue at some level unless a market driver (CO_2 price, regulation etc) is created.
2. *With many capture sites, cross-chain risks make contracting difficult*
   - Ideally each element of the CCS chain should only be financially exposed to its own performance, while still allowing for economies of scale to develop in the natural monopoly industries of transport and storage
3. *National Oil Companies have significant proprietary geological knowledge not accessible to others*
   - This knowledge should be leveraged when establishing storage, so other bidders making competition for provision of storage impractical

A successful business model will need to overcome any specific GCC challenges, alongside the general barriers to CCS development shown on slide 5

COMPETITIVE ADVANTAGES OF GCC CCUS

1. *Strong storage resource and extensive operational experience in gas handling*
   - Large land area and attractive geological formations, combine with extensive experience in oil and gas sector
2. *Track history of successful projects in conjunction with international partners*
   - Investors will see it as an environment with low policy and public risks.
   - In particular large and low cost industrial and power projects are regularly realised in the GCC
3. *Existing, trusted companies with significant government ownership operating as local monopolies in the oil and gas sector*
   - National Oil Companies have the competence to engage in CCS and a long term interest in making it a success
   - This may present an advantage to setting up monopoly CO_2 networks in the GCC compared to other regions

A successful business model should look to take advantage of the competitive advantages of the GCC region

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There are a range of potential drives for the capture of CO_2 being deployed globally from which a GCC approach can be selected

INTRODUCTION

- Many CO_2 emitting facilities are able to install carbon capture facilities that direct CO_2 to storage in order to reduce their emissions. For most commercial companies, the decision to do so requires an assessment that carbon capture and storage will be more profitable for the company than either continuing to emit CO_2; or taking other emissions reduction measures (e.g. renewable power, industrial process changes).
- Globally we see a range of primary commercial drivers for CCUS (see next slide), noting that some individual site may have multiple commercial drivers.
- A number of potential commercial drivers to carbon capture and storage are shown to the right. In our assessment, while all these could deliver value from CCS, high-emission companies are highly unlikely to decarbonise based on image (too costly) or for non-EOR CO_2 utilisation (value not achievable at the scales required for decarbonisation).
- Carbon border adjustments may drive CC for companies with large European export exposure, but are outside GCC control and unlikely to drive significant investment unless rolled out by additional jurisdictions. Direct GCC policies are therefore likely to be needed to drive CCS, and subsidies or CCS obligations would be most effective in the short-term.

POTENTIAL DRIVERS FOR CAPTURE OF CO_2

Current primary commercial drivers for CCUS

- EOR-led CO_2 utilisation
- Regulatory emission restrictions
- Direct grants to CCUS projects
- Direct capture subsidies
- Emission costs (carbon price)
- Storage subsidy (e.g. tax credit)

Possible new primary commercial drivers for CCUS

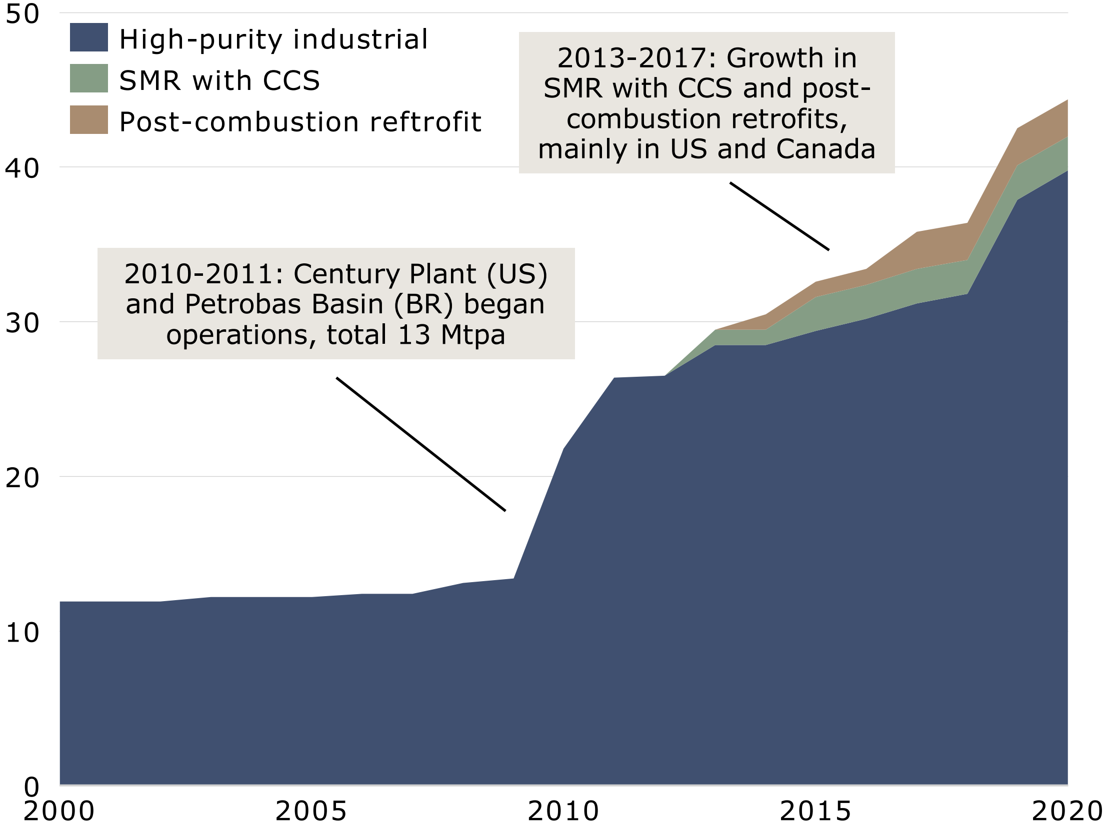
- Carbon border adjustments on exports
- CO_2 capture obligation on industry
- CO_2 storage obligation

Secondary drivers for CCUS

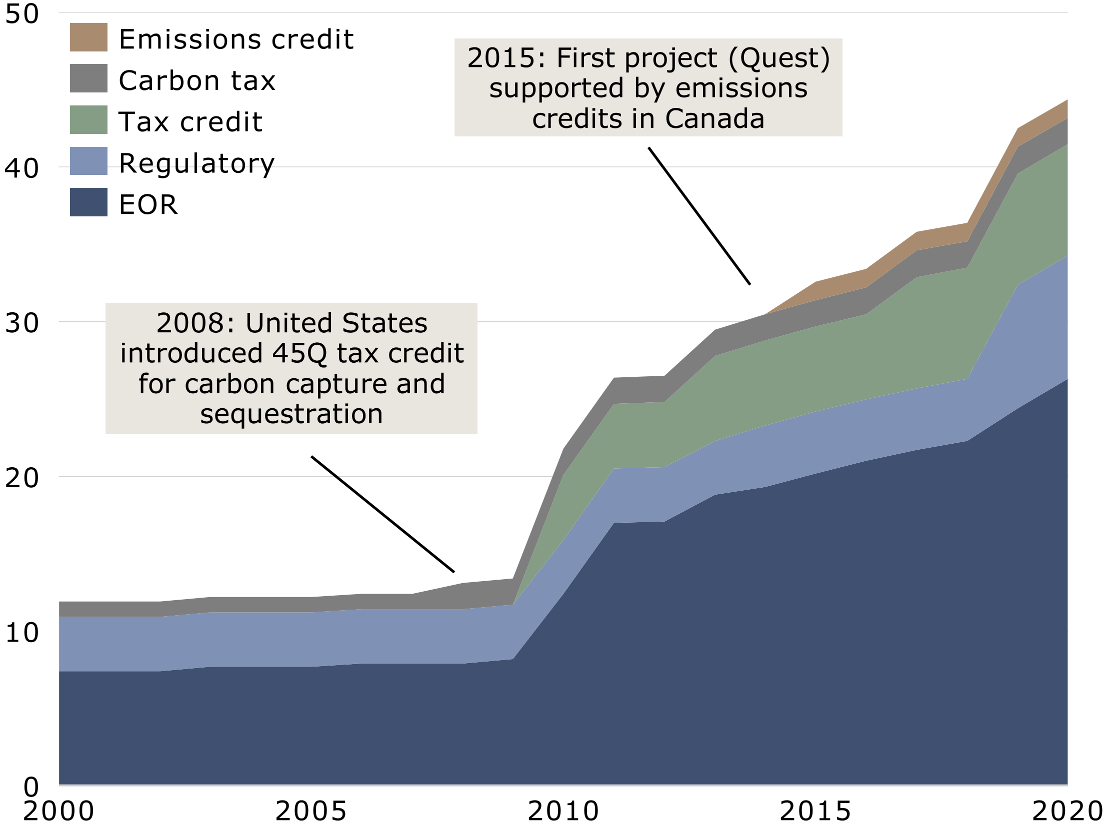
- Non-EOR CO_2 utilisation
- Corporate Decarbonisation & Image

Commercial CO_2 capture capacity increased by 273% since 2000, driven largely by enhanced oil recovery and introduction of tax credits

COMMERCIAL CO_2 CAPTURE CAPACITY BY TECHNOLOGY (Cumulative Mtpa)



COMMERCIAL CO_2 CAPTURE CAPACITY BY FINANCIAL DRIVER (Cumulative Mtpa)



Elements of a business model – shortlist of commercial incentives to capture and permanently store CO_2 in the GCC

COMMERCIAL DRIVERS

- Building on the range of options for a primary commercial driver in the GCC we present four broad options:
  - Government subsidies / taxation
  - CCUS obligation on National Oil Companies
  - Carbon market or emissions tax / obligation
  - CCUS obligation on electricity single buyer
- In this report we assume that one or more of these shortlisted options is chosen to create a primary commercial incentive for CCS in the GCC. We note that different options may be selected in each of the GCC countries for a variety of important local reasons.
- In all cases, an underlying ownership and contractual structure will be needed to define how capture, transport and storage are linked and how payments flow between the parties.
- Finally, an allocation mechanism will be required to ensure that economies of a project pipeline is created to capture economies of scale, attract the lowest cost financing and bring down costs over time.

SHORTLIST OF PRIMARY INCENTIVE STRUCTURES IN GCC

Government subsidies/ taxation	Government subsidies would match the approach being taken in Europe, with Norway, the Netherlands and the UK proceeding down this route, but require significant state subsidies.
CCUS obligation on National Oil Companies	A CCUS obligation on NOCs would direct a proportion of current revenues into a technology that may prolong their assets. Given these have significant state ownership, may be similar to government subsidies from a broader perspective.
Carbon market or emissions tax/obligation	Adding a price to carbon is generally viewed as economically efficient, charging emitters the social cost of their activities, but would be a significant change that may be politically difficult. An obligation on emissions would act similarly, and becomes a carbon market once emissions can be traded.
CCUS obligation on electricity single buyer	Regional electricity single buyers could be directed to only support new fossil generators that are fitted with CCS. Policy would charge associated costs onto consumers, but has no clear application outside the electricity sector.

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The components of the capture business model include allocation, payment and commercial structure – we consider 5 high-level models for the GCC

CAPTURE MODEL

Case	Summary description	Allocation criteria	Payment structure	Commercial structure
Auctioned IPP-style whole plant contract	Auctioned right to build, own and operate new plant with integrated CO_2 capture	Cheapest bid for new plant	Payments based on availability, production of product and fuel use	Single buyer (electricity, hydrogen or other)
Auctioning capture as a service	Auctioned right to build, own and operate capture facility to capture CO_2 associated with existing plant(s) processes under separate ownership	Bilateral low-purity CO_2 offtake agreements with plant owners. Auctioned right to build capture service	Payments base on availability, CO_2 captured and fuel used by capture process	Government body or National oil company
$/ton CO_2 payments	Competitive allocation of monetary support for owner of facility to add carbon capture capability	Cheapest CO_2 abatement cost amongst facilities of similar types	Payments based on CO_2 captured	Government body or National oil company
Fuel subsidies	Fuel provided at (substantial) discount to facilities that capture the CO_2 from their emissions	Flat rate or bilateral negotiation based on cost+	Discount applied to fuel volume proportional to CO_2 volume captured	National oil company
Carbon price/penalty	Cost charged to (some or all) carbon emissions of relevant sectors to incentivise decarbonisation	Fee applied to all facilities within a sector	Costs based on CO_2 emitted	Industries responding to policy (to avoid costs)

* Notes on revenue flow strongly tie in with who funds CCUS. The lists here nominally tie in to 'government funding'. Alternatives are discussed later in this chapter and could alter the revenue flows associated with each model.

Capture model assessment shows that an IPP-style approach has many potential advantages, but may only be applicable across an industry sub-set

CASE EVALUATION

Case	Competitive allocation	Avoids cross-party risk	Established mechanism	Applicable to industrial sectors	Incentives to minimise plant costs	Appropriate prices per industry[1]	Efficient allocation across industries[2]	Ease of implementation	Government controls process	Ability to mobilise private finance
✓ Auctioned IPP-style whole plant contract	●	●	●	○	●	●	◔	●	●	●
Auction capture as a service	●	○	○	●	●	●	◔	○	◕	◕
✓ $/tCO_2$ payments	◑	●	◕	●	◕	●	◑	◕	◕	◕
Fuel subsidies	◔	◕	○	●	◕	○	◕	◔	◑	◔
Carbon price / penalty	○	●	●	●	●	◑	●	○	◔	◑

Where IPP model does not work

SUMMARY

- Contracts based around the successful Independent Power Producer (IPP) model, with auctions determining who provides a service, will be effective where they can be applied.
- Where they cannot (products sold to market rather than a single buyer, i.e. most industrial sectors), a subsidy scheme paid based on CO_2 captured is our preferred model with a lower risk profile for CCUS delivery and investment than the alternatives considered.
- Preferred options are assessed in more detail in subsequent slides.

[1] Different industries have very different costs of capture. A high score here means that payments are reflective of the cost of capture, rather than over-rewarding cheap industries and under-rewarding expensive industries. Fuel subsidies would currently be unable to cover the costs of many industries and hence be ineffective. Although a carbon price is a blunt pricing instrument, as it charges a social cost for emissions it is not typically considered to "reward".

[2] Efficient allocation across industries refers to allowing the market to develop cheap industries/sites first, and expensive sites later.

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Deep dive into capture funding and allocation based on the IPP model shows that it is a good fit for some applications but not others

OVERVIEW

– The Middle East has a strong track record of low cost delivery of publicly tendered projects delivered by the private sector. Independent Power Producer contracts have successfully delivered gas, solar and nuclear power generation under a build, own and operate structure, with low risk contracts leading to low cost delivery to a single buyer of the product (electricity). Where IPP-style models can be simply applied to CCS projects, our recommendation would be that these be used as a basis for the capture stage.

APPLICABILITY OF IPP-STYLE CCUS MODELS

Key: Good fit | Limited applicability | Poor fit

Application	Fit	Assessment	Recommendation
Newbuild power	Good fit	Broadly, IPPs are already awarded to new power plants and could be used to fund new-build power plants with CCS, while the model would also fit well (where contracted to a single buyer) to independent construction of blue hydrogen production or direct air capture (for storage or reuse, such as into zero-carbon fuels). As in the power sector, we would expect these contracts to cover a significant period (e.g. 15-30 years) and include payments for plant availability, plant generation (of electricity, hydrogen, or the end product of DAC) and plant fuel use (or equivalently, provision of fuel).	IPP model should be taken forward as a 1st funding /allocation model applicable to a number of key industries
Blue hydrogen production	Good fit		
Direct air capture	Good fit		
Retrofit power	Limited applicability	Retrofitting power facilities already under IPP agreements may be more difficult because of the existing contracts in place. Negotiated agreements would be required to adjust these contracts and may not deliver value for money.	Likely that 2nd additional funding/ allocation model needed – see next slides
Newbuild industrial	Limited applicability		
Retrofit industrial	Poor fit	Industrial facilities are typically deployed with a variety of commercial customers, and in some cases a complex integration with the existing facility. An IPP-style agreement therefore seems impractical.	

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For non-power facilities, the IPP model does not appear a good fit so an alternative model will be required

BUSINESS MODELS: NON-POWER OVERVIEW

- Where most power-CCS subsidy models focus on private investment followed by performance payments (e.g. for time available, CO_2 stored and/or per MWh generated) over a 10-20+ year period, this model does not translate well to the industrial sector due to:
  - shorter investment horizons and uncertainty over long-term market conditions;
  - access to capital where the upfront investment is significant; and
  - potential delinking of production and carbon capture and the importance of carbon capture technical issues not disrupting existing processes, given international competition and lack of a captive market.
- An industrial business model needs to create a compelling business case that provides a reasonable rate of return on investment while de-risking business' carbon exposure – whether to international carbon pricing, consumer choice, or broader decarbonisation pressures.
- Business models supporting CCS on non-power facilities also need to cover a range of industries with very different costs, needs and expectations. The models used or proposed have tended to fall into one of:
  - cost avoidance (e.g. carbon prices in Norway for Snøhvit and Sleipner);
  - direct subsidies to capture CO_2 or produce low carbon product (e.g. UK, Netherlands, Norway Longship);
  - value or subsidies based on CO_2 stored (e.g. USA 45Q and EOR models) or otherwise used (e.g. commercial CO_2 sales); or
  - regulations or emissions requirements (e.g. Gorgon in Australia).
- Based on the range of options considered globally we outline a alternatives for the GCC on the following slides.
- This short-list of options for all focus on providing a subsidy to cover the cost of carbon capture at industrial facilities in the GCC. Based on current carbon pricing and industrial policies we assume there is relatively little appetite cost or regulation based mechanisms which could create disincentives for regional industrial growth.

Key considerations for non-power subsidy-based business models hinge on risk sharing and funding structures that enable capital recovery

CONSIDERATIONS FOR SUBSIDY-BASED BUSINESS MODELS

Performance-linked payments to recover private capital investment

Upfront co-funding to reduce initial investment requirements

Risk sharing that leaves incentives in place but avoids crippling penalties

Long term payment streams to encourage continued use of CO_2 capture

Short term payments to allow quick recovery of (some or all) capital investment

CONSIDERATIONS FOR THE GCC

- Upfront co-funding (e.g. grants) has been used in Norway and the UK and reduces financing requirements. Given the favourable investment conditions in the Middle East this should be low priority for the GCC, but could be considered if consultation suggests it is needed.
- A wide range of risk-sharing exists between models, with Norway covering nearly 80% of capital overruns compared to no such mechanism in the UK or Netherlands. The UK has generous terms allowing full (albeit delayed) capital recovery with 50% capture performance, while in most other models there are stronger penalties for low performance. We make suggestions for the GCC on the next slide.
- A split between short term capital recovery and long term payments to incentivise continued operation is used in the UK and would be beneficial for the GCC, to balance shorter-term investment horizons with the expectation that support delivers a CCS facility that captures CO_2 for a substantial period. The UK model repays CAPEX with a five year payment stream with a longer (10+ year) payment covering OPEX. A similar model published by AFRY (previously) Pöyry with the Tees Valley Combined Authority repaid most CAPEX within five years, with OPEX and the remaining CAPEX covered under a longer term payment.

For industries where an IPP model is not appropriate, we recommend a model based on a bilateral approach, with competition between similar sites

OVERVIEW AND NON-POWER RISK SHARING

For industries where an IPP model is not appropriate we would recommend a business model based on:

1. Bilaterally agreed strike prices per tonne CO_2 captured, with payments designed to cover costs and a reasonable return, and competition between similar types of sites based on costs and return required
   - Either a model using a short-term (e.g. 5 years) payment repaying capital expenditure, coupled with a long-term (e.g. 15 years) payment covering operational costs and a reasonable return on investment; or alternatively a simpler single level payment for a 10-15 year period.
2. Risk sharing consisting for capture plant capex and opex:
   - Re-openers if operational costs differ substantially from pre-contract expectations, allowing pain/gain sharing from either unexpected costs or future efficiency developments, due to the relatively low current certainty over such costs and peripheral nature of CCS to most industries it will be fitted to.
3. T&S risks under-written by government; i.e. industry would still get their capital investments repaid if the transport and storage network was delayed or unavailable when required.
4. Construction and performance risks covered by default by industry, as:
   - these risks are within the control of capture sites and their technology providers; and
   - further expected deployment in Europe and the US, as well as the Middle East, should rapidly de-risk technology and allow these risks to be covered.
   - We note that rapid CCS development might mean some risk sharing on capital cost overruns is needed for first moving sites, such as the proposed Jubail hub, when the technology will have a high perceived risk. Requirements here will be revealed in discussions with the industries involved but expecting these risks to be largely or fully covered by industry seems a reasonable default.
5. Adjustments for any transport and storage fees due and, in the event of a carbon price being applied to the region, for carbon price savings (e.g. “contract for difference”).

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Given the need for coordination and long-term planning among stakeholders, transport and storage supply chain tends to be partially or fully integrated

OVERVIEW

- The transport part of a CCUS chain typically moves CO_2 from capture facilities to storage (or utilisation) facilities. Depending on circumstances, it may involve pipe or ship transport, purification, compression and/or liquefaction facilities, and small-scale temporary storage. This typically involves different actors to those capturing CO_2, and so most CCUS business models assume transport and storage (T&S) is owned and operated by a different party to CO_2 capture, with resultant cross-chain business risks. Supporting separate ownership also allows for CCUS "hubs" involving multiple capture facilities with different owners.
- Although transport and storage may involve different skills, in many CCUS business models, they are either partially or fully integrated (e.g. the UK and Norwegian schemes) as this helps facilitate coordination and long-term planning between the two sectors.
- For the GCC, we expect the default option to be transport via pipeline to on- or off-shore storage facilities. CO_2 transport via ships may also be present in various forms (e.g. domestic, international).

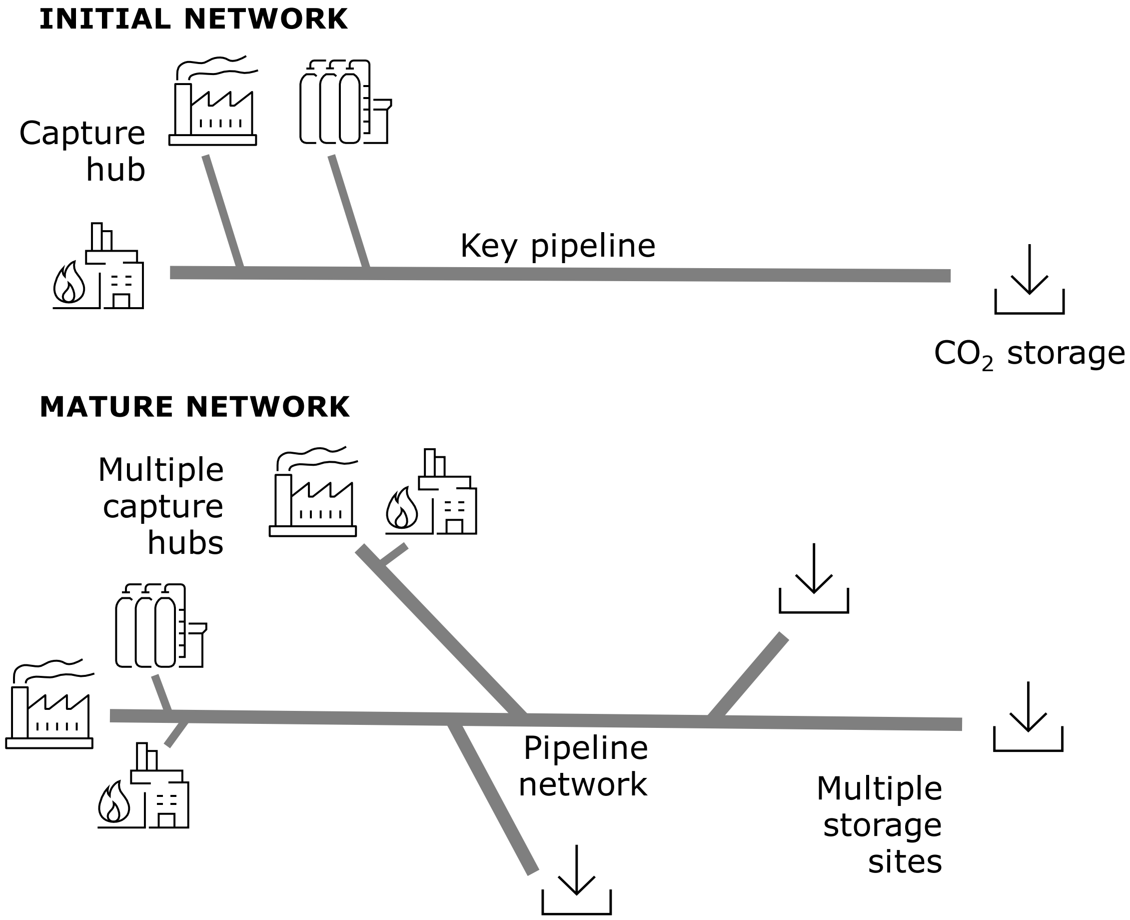
BUILDING BLOCKS

Ownership	– Monopoly or multiple owners in competition – Transport and storage have same or different owners
Operation	– CO_2 dispatch decisions by owner or separate body
Network Design	– Decisions on store and pipe expansions made by owner or separate body
Revenue Structure	– Grant / fixed / performance payments – Capacity versus commodity and penalties
Revenue Stream	– Funded by capture sites or direct from "CCUS funding body"

A range of theoretical options exist for ownership and operation of the CO_2 transport and storage network, but NOCs seem very well placed

OWNERSHIP AND OPERATIONS

- The presence of National Oil Companies (NOCs) experienced with pipelines, shipping and subsurface geology suggests they would be capable of building and operating both transport and storage infrastructure.
- Alternatives include:
  - Competitive allocation of storage sites, with each storage site potentially operated by a different owner.
  - Competitive allocation of pipeline transport for initial networks, with facility made for extending or modifying contracts to incorporate future network expansions (whether by the same party, or a new party).
  - Day-to-do operations would typically be controlled by the transport owner, but this may become a separate role if a network incorporated transport elements with different owners.
- We would typically expect political and commercial issues if NOCs were forced to transfer information about subsurface geology, making competitive allocation of storage in particular a difficult model. We present it here as a theoretical option.



The overall Transport and Storage business model also needs to consider the revenue source and the structure of the revenue stream

REVENUE SOURCE

- T&S networks can receive revenue direct from capture sites (either local or through imports), via direct funding of the T&S sector, or from CO_2 sales (e.g. for Enhanced Oil Recovery).
- CO_2 use for EOR has driven the Abu Dhabi and Uthmaniyah projects and may continue to be significant compared to T&S costs, but are unlikely to fund a broad CCS rollout.
- Revenue from capture sites is common in Europe, often with government covering coordination risks. This structure lends itself to conversion to a “merchant model” in future when carbon price savings cover full costs. In the GCC, lack of a carbon price means significant economic structural changes would be needed to convert to a capture-site funded merchant model and direct funding may be more appropriate.

REVENUE STRUCTURE

- To minimise cross chain risks, the basic revenue structure should reflect costs:
  - One set of payments to cover capital expenditure and the cost of making the network available for use
  - A cost-reflective payment stream associated with CO_2 transported and stored
- Contract structures based on payment for performance (availability and delivered volumes) are common in the GCC, such as IPP contracts in the power sector. These provide appropriate performance incentives and suggest payment structures based on availability and delivered volumes.

Components of T&S business model include ownership, network design and commercial structure – we consider 5 high-level models for the GCC

<table>
<tr><th>Case</th><th>Ownership</th><th>Network Design</th><th>Operator</th><th>Revenue flow*</th><th>Revenue structure</th></tr>
<tr><td>Direct NOC Ownership</td><td>T&S fully owned by NOC</td><td>NOC determines network planning</td><td>CO_2 dispatch decisions by NOC</td><td>Direct funding to NOC</td><td rowspan="5">For all cases:

Availability payments based on capacity technically available.

Utilisation payments based on CO_2 transported / stored

Minimum performance levels and associated penalties for:
- Annual availability
- Fugitive CO_2 emissions
- CO_2 store leakage</td></tr>
<tr><td>Independent storage operations</td><td>Transport owned by NOC. Storage competitively allocated to Independent Storage Providers</td><td>NOC determines network planning, potential for competition between ISPs at different storage sites</td><td>CO_2 dispatch decisions by NOC</td><td>Direct funding to NOC and ISPs or direct funding to NOC who handles payments to ISPs</td></tr>
<tr><td>Independent transport operations</td><td>Storage owned by NOC. Transport competitively allocated to Independent Transport Provider</td><td>NOC determines network planning although ITPs may have a role in choosing pipe routes</td><td>Transport operator determines CO_2 dispatch. NOC may be able to specify stores to use.</td><td>Direct funding to NOC and ITPs</td></tr>
<tr><td>Independent Monopoly</td><td>T&S competitively allocated under RAB style model</td><td>Allocation body to determine T&S requirements</td><td>CO_2 dispatch decisions by monopoly</td><td>Direct funding to monopoly</td></tr>
<tr><td>Market transition</td><td>Competitive allocation to providers of T, S or T&S services</td><td>Allocation body to determine T&S requirements</td><td>Transport operator determines CO_2 dispatch; either first ITP or separate body</td><td>Capture sites pay for T&S service. Revenue re-allocation between network owners</td></tr>
</table>

* Notes on revenue flow strongly tie in with who funds CCUS. The lists here nominally tie in to 'government funding'. Alternatives discussed earlier in this section would alter the revenue flows associated with each model.

Transport and storage model assessment shows a direct NOC ownership model would have advantages although precludes competitive allocation

Case	Removing cross-chain risk[1]	Competitive allocation[2]	Operational complexity	Flexibility to expand	Delivery incentives[3]	Clean fossil utilisation[3]	Need to create new bodies	Use of existing knowledge[4]	EOR Coordination	Cross-border complication
✔ Direct NOC Ownership	●	○	●	●	●	●	●	◕	●	◑
Independent storage operations	◕	◑	◕	●	◕	◕	●	◑	◔	◑
Independent transport operations	◕	◑	◕	◑	◕	◕	●	●	◕	◕
Independent Monopoly	●	◑	●	◑	◕	◕	○	◑	○	◕
Market transition	◕	●	◔	◑	◕	◕	○	◑	◔	◕

SUMMARY

- In our view, T&S monopolies based around the existing National Oil Companies look most attractive, utilising existing subsurface knowledge and putting the responsibility for enabling CCUS on large, locally-trusted organisations that have a long-term incentive to make CCUS happen.
- We look in detail at the preferred solution in the following slides

Notes:

- [1] Performance based funding means low cross-chain risk but combined ownership remains the lowest-risk option
- [2] An independent monopoly can be competitively allocated for the initial deployment, but then has no competitors for subsequent developments.
- [3] Contract structures will incentivise performance in all models; however the NOCs have the greatest incentive to plan and develop CCUS as a whole due to the benefits to the tie-ins with their fossil operations
- [4] The NOCs have substantial existing knowledge of the subsurface space that can be leveraged for CO_2 storage operations. While they also have transport capabilities, there may be additional international expertise in that area.

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NOCs seem well placed to operate both part of the network, with some options around cost recovery approach

KEY POINTS

- Transport operations lend themselves to monopoly models, due to inefficiencies of multiple networks covering a single area, and complications at interfaces between connected networks. Construction of an initial network could be auctioned under an independent provider model, and may attract investors experienced with CO_2 transport. This would present complications when the network needs to be expanded, as competition would be limited and there would be less flexibility in network expansions.
- While storage sites could be centrally auctioned to independent operators, the National Oil Companies (NOCs) have substantial existing knowledge that would be difficult to force them to share. This should be utilised, suggesting that NOCs are best placed to handle CO_2 storage operations.
- A NOC monopoly model performs well against most assessment criteria, minimising cross-chain risk, maximising expansion flexibility and incorporating companies that have a vested interest in broad development of CCS.
- Requirements to ensure fair access will be needed to ensure capture sites have confidence that their investments will be connected to T&S.

SUMMARY

- Our recommended model would be:
  1. a single owner and operator handling both storage and transport.
     - In nations with potential CO_2 storage sites, the National Oil Companies (NOCs) would be the preferred choice to own and operate T&S networks.
     - In nations without CO_2 storage, the single owner could be either the NOCs or an independent provider competitively awarded.
  2. Typically a regulated asset base (RAB) model is likely to be lowest cost if the network is funded externally. Total revenues would then be fixed at an allowed level.
     - Revenue streams should be cost reflective (availability and utilisation payments) as is already standard in the region (for example for IPPs in the power sector).
     - Depending on the funding framework and sources, regulatory structures may be needed to assess allowed revenues and performance and review potential expansions.

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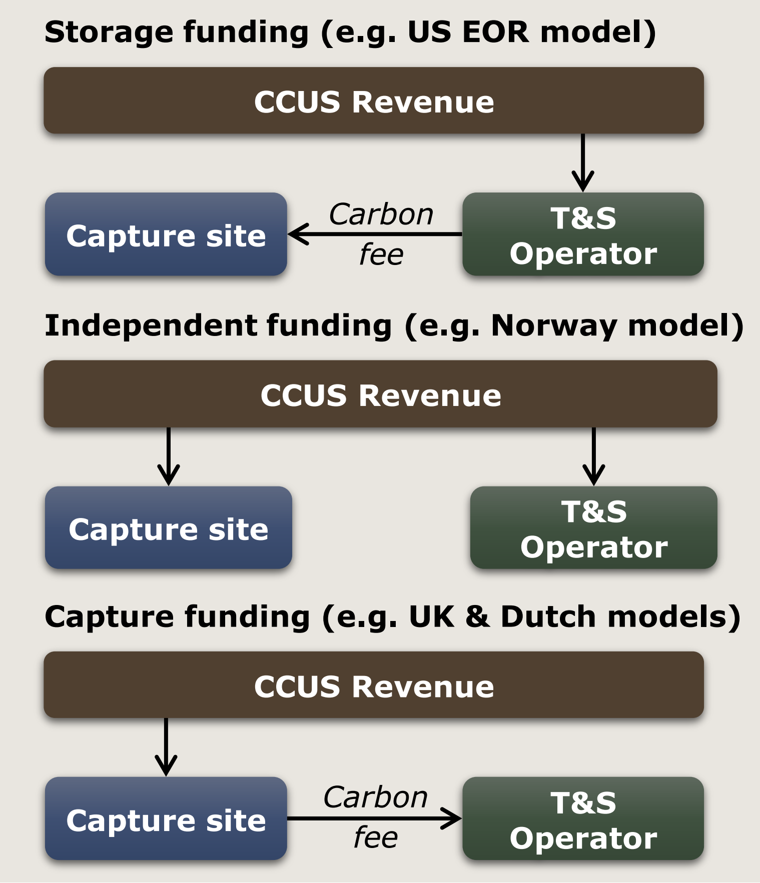
While not necessary under direct funding of T&S there are economic advantages to access fees into the revenue model as the system grows

T&S ACCESS AND REVENUE

- T&S operators will need to continually co-ordinate with capture sites for safe operation of the network. Third party access obligations would be expected to both ensure fair access and provide certainty to potential capture projects as to how and when they will be able to connect to the T&S network. While detailed terms are beyond the scope of this work, we would expect geographic restrictions based on network coverage and expansions, and technical requirements for CO_2 injected into the network.
- Transport and storage operators may also have a commercial relationship with capture sites with payments between them. Three types of model (and blends thereof) have been proposed depending on circumstances.
- Generally, capture funding models are good at revealing the full costs of CCS with geological storage, and work well when there is a strong economic incentive to decarbonise such as a significant carbon price. While the GCC has no such incentive, an independent funding model is attractive as it avoids counterparty and volume risks associated with payments between parties.
- While there is no necessity for a T&S payment/fee, they
  - allow for geographic price signals where efficient project allocation is seen as important;
  - provide reference access prices that could serve as a useful starting point for international imports (both between GCC countries and outside); and
  - provide a route to merchant build without subsidy when an economic driver for CCS is present (e.g. independent DACCS projects).

In summary, payments for the T&S service are not initially required, but they should be considered as the industry matures.

COMMERCIAL RELATIONSHIP MODELS



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CO_2 imports provide a potential for the GCC to further monetise their storage resources, so the business model should allow for that development

CO_2 IMPORTS – OVERVIEW

- The GCC region has the potential to import CO_2 for a fee, in essence "exporting CO_2 storage" to customers in regions with little or no CO_2 storage of their own. Typically CO_2 import terminals would pass CO_2 to a pipeline network for subsequent pipe transport and storage, although ship-to-store schemes have also been proposed for offshore storage, bypassing pipeline transport.
- Users would pay a volume fee for delivering CO_2 to be stored, either to receiving terminals in the GCC, or to ships or terminals in other regions. We expect this fee would be on a commercial agreed basis that would allow for a profitable new industry.
- It is likely to be simplest to cover foreign CO_2 export terminals and shipping under separate business structures to T&S, even though in the early days of CO_2 storage NOCs may need to coordinate shipping. The T&S company would then receive a fee from the shipping operator delivering CO_2 to import terminals.
- Various business model options exist within this broad framework:
  - Import terminals could be owned by the T&S company, or independently with the T&S company obliged to provide a connection under third-party-access rules with obligations to transport the CO_2.
  - Shipping (and CO_2 export facilities in other regions) could be operated by the import terminal owner, or independently.
  - The import fee received by the T&S company could be set by the T&S company or a regulator.
  - If the T&S company is externally funded, import fees could either be fully included within their allowed revenue, or included only in part to give them an incentive to market and sell a CO_2 import service.
- Allowing import terminals to set import fees is likely to more effective at encouraging CO_2 imports than regulated fees, but will only be effective if they benefit from this revenue. That would suggest that either the import terminals should be independent and required to pay a regulated access fee to T&S, OR that the import terminals be part of the T&S network, with some financial benefit (beyond RAB recovery) from imports, and freedom to adjust fees.

Noted that 'CO_2 import' could apply to 2 different cases for GCC countries:
1. Within GCC countries where country X builds the T&S infrastructure and allows other GCC countries to pipe their CO_2 through network.
2. International CO_2 import. A CO_2 import terminal and pipeline network may be needed.
This slide is primarily concerned with the second of these options, with cross-border transfer of CO_2 within the GCC considered elsewhere.

COP26 established clear accounting rules for emissions transfers between countries

ARTICLE 6.2 –RULES FOR TRANSFERS BETWEEN COUNTRIES

- Article 6.2 enables countries to establish bilateral or multilateral ‘cooperative approaches’ to trading credits (in this context called Internationally Transferred Mitigation Outcomes, or ITMOs), in order to meet their decarbonisation targets.
- Crucially, it provides accounting standards for transfers between countries, which reduce the scope for any double counting of ITMOs.
- The key accounting concept is ‘**corresponding adjustment**’. In essence, the country receiving the ITMO subtracts the relevant amount of carbon from its total emission levels, but the country transferring the ITMO will have to add the same amount to its own total. So only the country that receives the ITMO can benefit from the ITMO in its carbon accounting.
- Article 6.2 transactions are not governed by a central UN authority, but are regulated by bilateral agreements. However, there are various reporting requirements, and the creation of an international registry, an Article 6 database and a centralised accounting and reporting platform has been agreed.

WHAT IT MEANS FOR THE GCC

- These developments mean there is a formal route for countries to buy ‘CO_2 import and storage as a service’ from GCC countries, in the form of bilateral agreements.
- It would enable countries buying the service to subtract the relevant amount of carbon from its total emission levels.
- In return, the GCC country carrying out the service would have to add the same amount to its own total and therefore find additional sources of emission reduction if it were to maintain alignment with it’s own commitments under the Paris Agreement.
- In addition to trade via bilateral agreements, it is also possible to sell ‘CO_2 import and storage as a service’ via carbon credits as discussed in the next slide.

It may be possible to seed the CO_2 storage market by selling voluntary offset credits. Please see the section on Carbon Removals (Chapter 9) for more details.

COP26 also resulted in a agreement to launch a new international crediting mechanism

ARTICLE 6.4 – A NEW INTERNATIONAL CREDITING MECHANISM

- Article 6.4 establishes an international carbon market system, to be governed by a **central supervisory body, whose role will include approving the methodologies** that can be used to generate mitigation outcomes, establishing a **central registry and accrediting national supervisory bodies**.
- It is a framework within which countries can create their own markets, establish rules and enforce penalties, so there may be some significant differences between markets operating under Article 6.4.
- Bodies established by host nations will approve and authorise projects for inclusion in the system, assuming they comply with the criteria established by the central supervisory body and any additional local requirements.
- For Article 6.4 credits to be traded internationally, host nations will have to make corresponding adjustments, as they do under Article 6.2. Businesses will be able to participate in the system.
- The new system will not be fully operational for some time, not least because the supervisory body – which will meet at least twice in 2022 – needs to resolve questions of methodology and administration.

WHAT IT MEANS FOR THE GCC

- Assuming CCUS technologies are deemed eligible under the rules of the new scheme (and we assume they will be), credits will be issued to projects in GCC nations.
- These credits can then either be sold:
  - to national governments, in which case, the host nations will have to make corresponding adjustments; or
  - to businesses who want to claim progress towards their own decarbonisation targets. The agreement at COP26 does not specify if this trade should be subject to a Corresponding Adjustment. Time will tell how the private-sector reacts to this choice; we expect trades with or without Corresponding Adjustments will occur for some time. Credits with a Corresponding Adjustment are likely to trade at a premium to those without because it allows the business to make a concrete claim, without being accused of emission reductions being double counted.
- In addition to this new UN backed scheme, voluntary Standard Organisations could issue credits to CCUS projects. Gold Standard has said it will phase in the use of offsets that come with a Corresponding Adjustment, whilst VCS (another leading standard) has reported that they will not.

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Integration of EOR into a NOC monopoly model is relatively straight-forward, with different implications whether T&S is funded internally or externally

ENHANCED OIL RECOVERY – OVERVIEW

- Carbon Capture and Storage has historically been largely supported by revenues from Enhanced Oil Recovery (EOR), with the majority of operational projects gaining revenue from using captured CO_2 for EOR. Given the large oil and gas resources in the GCC region, and successful projects at Abu Dhabi and Uthmaniyah, it is likely that CCS will create future EOR opportunities in the region. This is likely to be at lower volumes than needed for decarbonisation; i.e. geological storage will be needed as well.
- Integration of Enhanced Oil Recovery into a NOC monopoly model is relatively straight-forward, with slightly different implications depending on whether T&S is internally or externally funded.

NOC FUNDED TRANSPORT AND STORAGE

- In the case where National Oil Companies cover the costs of CCS themselves, no particular arrangements need to be made for Enhanced Oil Recovery; this becomes an option for each company to use to recover revenue from the T&S network.
- Decisions on the use of Enhanced Oil Recovery would be up to each NOC on a commercial basis.

EXTERNALLY FUNDED TRANSPORT AND STORAGE

- Where a monopoly T&S provider operates under an externally funded RAB model, provision should be made for:
  - Third party access to CO_2 if beneficial for EOR operations;
  - Revenue recovered from EOR would be included within the RAB cost base, and hence would lower users' fees.
- In this case, agreements would be needed as to the price an EOR operator should pay for the CO_2. A regulatory/policy position on how EOR benefits should be calculated and split will be needed; commercial arrangements are unlikely to be sufficient due to weak pricing incentives under a RAB model and conflicts of interest in the NOC monopoly model where both the T&S and EOR operations would be under the same owner.

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CO_2 transportation across national borders presents significant benefits; however, the decision will largely be a political and commercial one

CROSS BORDER TRANSPORT - OVERVIEW

- The simplest NOC monopoly model would consist of a separate network and asset base exist within each GCC country. However, there are likely to be significant benefits from transporting CO_2 across national borders; in particular the best storage formations are predominantly located in Saudi Arabia and Oman.
- Cross-border CO_2 transport for offshore storage is currently blocked for most countries by the London Protocol; an amendment from 2009[1] to allow it must be ratified by two-thirds of signatories to enter force. A resolution from 2019[2] allows for provisional application of the amendment between any two states that have approved it. CO_2 transport between GCC nations would therefore require them to ratify the 2009 amendment at least if offshore storge is envisaged; we assume that this will be done prior to any such transport occurring.
- Various business models for cross-border transport are possible:
  - Expansion of the T&S network across national borders under a single owner. E.g. a GCC NOCs T&S network could extend into neighbouring countries, collecting CO_2 directly from local parties.
  - Shared ownership/operation of a multi-country T&S network through a joint venture of the different National Oil Companies involved.
  - Domestic ownership with border agreements governing terms for the handover of CO_2 where networks meet at national borders.
  - Any combination of the above.
- We consider that the choice between these options is largely a political and commercial decision between the parties involved. In all cases, we discuss certain principles that should be applied on the next slide.

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Cross border transport fees are typically recovered through three unique fee structures that reflect the cost of operating a T&S network

CROSS BORDER TRANSPORT – FEE OPTIONS

- CO_2 storage is a service. Where one country exports CO_2, the importing country will incur a cost for transporting and storing that CO_2. This would typically be recovered through access charges to the CO_2 T&S network. Different approaches may be used to set international fee levels:
  1. Network average long-run cost recovery. This would seek to recover the "fair share" of total network costs based on CO_2 capacity and flows. Cost recovery would be evaluated in the same manner as allowed RAB revenues, and hence be very similar to charging international access the same fee as unsubsidised domestic access (i.e. if allowed revenue was fully recovered from users).
  2. Marginal expansion cost recovery. This would seek to recover additional long-run costs associated with expanding the network to support international CO_2 volumes, assuming the domestic network would exist and be paid for regardless. Typically unit costs decrease as networks expand, so this would usually result in a lower fee than network average long-run cost recovery.
  3. Commercially agreed fee. This would typically be a higher fee than the cost recovery options, to create value for the importing country from exploiting their CO_2 storage resource, and could parallel the assumptions under "CO_2 imports".

CROSS BORDER TRANSPORT – FURTHER CONSIDERATIONS

- Marginal cost recovery may be seen as subsidising imports ahead of domestic use. If RAB costs were recovered from network users, this approach would typically result in international users paying a lower fee than equivalent domestic users. Long run cost recovery is a more balanced position - while it may help recover covers costs associated with setting up the initial network, the exporting country benefits from that network alongside the importing country.
- A commercial fee above cost allows the importing country to benefit directly from their CO_2 storage resource. The decision between these approaches is a commercial and political one, with the pure cost recovery approach likely to be most favourable to CCS deployment.
- In either case, consideration should be given to making charges cost-reflective of running a T&S network: that is, split between availability and utilisation tariffs, with most costs recovered through availability fees.

CCUS business models will likely continue to evolve over time with changing technical and market risks as well as general sector maturity

EVOLUTION OF CAPTURE FUNDING

- Business models for CCUS are often designed to develop over time, as technical and market risks reduce and the sector matures. In Europe, for example, the long-term goal is to remove subsidies and create a market where merchant CCUS can be deployed based on the carbon price; existing business models reflect the reality that this does not yet work commercially, and support will be needed in the interim.

- In the GCC, exports of hydrogen and direct air capture products (removals or zero-carbon fuels) may attract significant revenue from providing those products/services over time. Other industries may develop markets for low-carbon products depending on consumer preferences in export markets. As we expect these incentives to change over time it makes sense to also plan for the business models evolution over time.

- As the market changes, the business model may be structured to adapt:
    1. A carbon price would affect incentives on industrial capture sites. Ultimately a carbon price may allow for deployment of CCUS on certain industries without subsidies, but support structures will be needed until prices exceed CCUS costs. However, in the interim contracts may be structured to recoup most or all of any carbon savings from CCS that arise from any support payments that were originally structured without them.
    2. The development of a large market for zero-carbon goods would reduce or eliminate the need for industrial support in related sectors. While this need not trigger a change to the support structures, it would be best dealt with by maintaining elements of competition in allocating support between similar sites to ensure that this benefit remains visible and support is not larger than necessary.
    3. Once some categories of build approach profitability, it may be advisable to expose capture to a fee to utilise transport and storage. This option could be present initially, or brought in at a later date, and is discussed further in the transport and storage section.
    4. Contract re-openers around opex costs could also be removed – this would put more risk on the CCS developer but would in turn encourage innovation and further cost reductions (once initial cost risks have reduced).

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CO_2 leakage poses a particular risk of undermining the environmental benefits and rationale supporting carbon capture and storage projects

CO_2 LEAKAGE – OVERVIEW

- The environmental benefits of carbon capture and storage are heavily reliant on the permanency of the CO_2 storage. Leakage undermines the rationale for engaging in CCS, particularly if it occurs at a significant level (e.g. >1% of stored CO_2).
- Leak avoidance is predominantly driven by geology and hence choice of injection sites, as well as well design and management. While leakage is rarely predicted, leakage risks are hence strongly influenced by choices made by the CO_2 storage company. Leak detection depends on monitoring regimes, and while active wells are typically monitored and monitoring technologies are developing rapidly, there remains a significant cost to monitor abandoned wells for CO_2 leakage and particularly to track the ongoing dispersion of CO_2 underground. This is expected to lead to tension at the end of an injection site's life, between minimising costs and monitoring the permanency of the CO_2 storage.
- In the EU, a financial penalty exists for leakage as it is assessed under the EU ETS, and is a significant risk in assessing commercial ventures. In the absence of a GCC carbon price, there is no direct financial incentive to avoid leakage, although a number of parties (e.g. capture sites, CO_2 exporters, NGOs) will want guarantees that leakage is low. GCC national governments also have an incentive to ensure low leakage in order to meet their climate NDCs, given that CO_2 leakage is assessed in greenhouse gas accounting frameworks.
- Finally there is likely to be a commercial benefit for minimising leakage for the capture projects if a market develops for low-carbon products or negative emissions. This may come for example from minimum standards for storage, or through a market-style approach like a carbon border adjustment mechanism with leakage from storage accounted for in carbon accounting.
- While a detailed framework is beyond the scope of our discussion here, we suggest that there should be:
  - Minimum requirements on monitoring for CO_2 leakage both to assess leakage rates and allow early intervention when possible.
  - Financial consequences to leakage when storage companies have been paid to store CO_2.
  - Consideration of independent leakage assessments, which would engender international confidence in the robustness of GCC storage for either CO_2 imports, or hydrogen, zero carbon fuel or CO_2 removal exports, when these are based on an assumption of permanent CO_2 storage.

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There are a range of business models emerging globally that offer lessons for the GCC and can help drive a successful CCUS roll-out in the region

BUSINESS MODEL CONSIDERATIONS

The GCC region already has four CCUS projects, but deploying CCUS at large scale will require a commercial driver.

Globally Enhanced Oil Recovery has been the strongest commercial driver for carbon capture and storage, although a number of new business models are emerging which are looking to significantly accelerate deployment.

While the GCC lacks a strong commercial driver for domestic decarbonisation (e.g. a carbon price or emission limits), there is significant ambition to bring forward CCUS as part of a circular carbon economy are a number of routes to create such a driver:

- Direct investment or subsidies for CCUS development from the government;
- Direct investment or subsidies for CCUS development from national oil companies,
- A system of carbon pricing/penalties; or
- CCUS obligations.

- Getting the ownership structure, revenue streams and incentive structures right can help CCS to develop successfully, opening up economies of scale from sharing common infrastructure between different capture projects and across borders. Unsuitable business models can increase costs and result in less or no CCS development.

RECOMMENDATIONS

Building on models being developed elsewhere we recommend that:

1. the chosen business model separates out capture from transport and storage side, to alleviate cross-chain risk and allow for the rapid capture of economies of scale in CO_2 transport and storage;
2. the Independent Power Producer (IPP) model used successfully within the GCC electricity sector be utilised as a trusted business model for capture where applicable: electricity production, hydrogen production and potentially direct air capture where a single buyer model can be used.
3. For most other industries, a business model consisting of direct payments linked to the volume CO_2 captured be used, with risk shares insulating industry from delays or failures in transport and storage,
4. National oil companies are given the role of single owner/operator of the transport and storage of CO_2, given their skills, resources, and detailed knowledge of the subsurface geology of the region.
   - Consideration should be given to cost-reflective charging for transport and storage access in the longer term, particularly as it relates to simplifying cost signals for international imports.
   - CO_2 imports from outside the GCC should be anticipated and charged an import fee for access to the T&S network.
5. Cross border CO_2 transport within the GCC could be handled in a number of ways, and the choice between options is largely political. Early negotiations to reach a trading framework early on would ease subsequent deployment.

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CHAPTER 7

Cost Reductions

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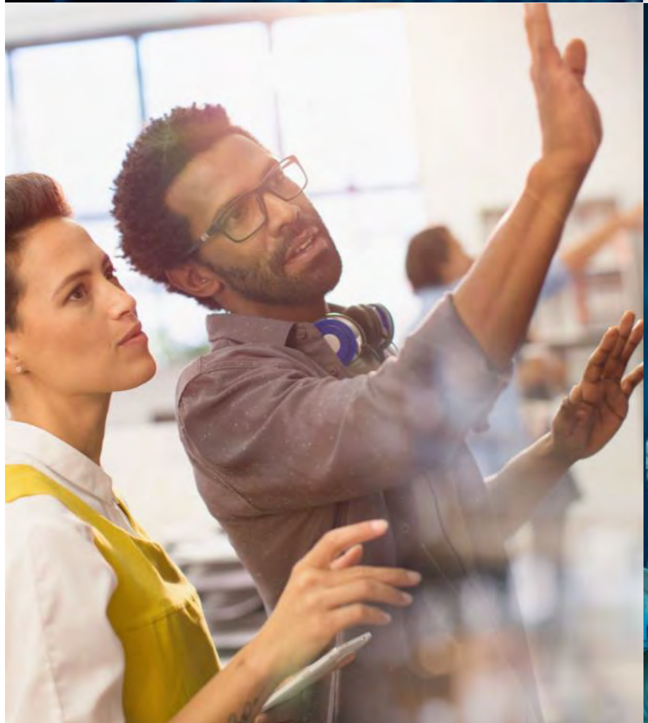
7. Cost Reduction



CCUS cost reduction drivers show opportunities for economies of scale, process optimisation and reducing risk perception in financing alongside R&D

CAPTURE TECHNOLOGY SUMMARY

- Scale and CO_2 content (partial pressure) of gas stream are fundamental cost influencers for capture across different industries
- However significant opportunities for driving down costs and shortening project deployment timelines
- The primary drivers for capture cost declines for 'current' capture technologies will be CCUS roll-out, which through successive generations of CCUS projects, will facilitate **learning-by-doing** leading to gains from:
  - Economies of scale [mainly captured @1mt$CO_{2/yr}$ scale]
  - Reduced redundancy and contingency
  - Modularisation
  - Heat integration
- Due to the capital-intensive nature of capture, cost savings significantly enhanced through falling financing costs – should arise from a **reduction in technology/policy risk perception**
- **Continued R&D** will enable next generation technologies to move on from the near-commercial pipeline (advanced chemical solvents, high CO_2 permeance membrane etc.) that could ultimately be more cost effective and efficient in capturing CO_2 (lower energy penalty)

Cost declines in capture can typically be regarded as global, in that once realized in one location they should quickly be available in others

TRANSPORT AND STORAGE SUMMARY

- On the Transport and storage costs are highly variable in the literature varying by a factor of 10, driven primarily by:
  - Transport distance (from capture to storage)
  - Transport volumes
  - Transport option (pipeline vs shipping)
  - CO_2 storage site characteristics (characterisation level, on/off-shore volume and injectivity)
  - Business model approach (direct funding of a hub vs trickle down model) pushing risk on different parties
- Rather than technology innovation (as technology steps largely mature) the main drivers for T&S cost declines come through:
  - Economies of scale [savings up to 20-30mtCO_2/yr scale]
  - Storage risk perception
  - Policy risk perception
- Exceptions include CO_2 transport via ship and monitoring and verification of CO_2 storage both of which are relatively immature

Cost declines in transport and storage can typically be regarded as local, as largely driven by decisions taken at a project/hub level

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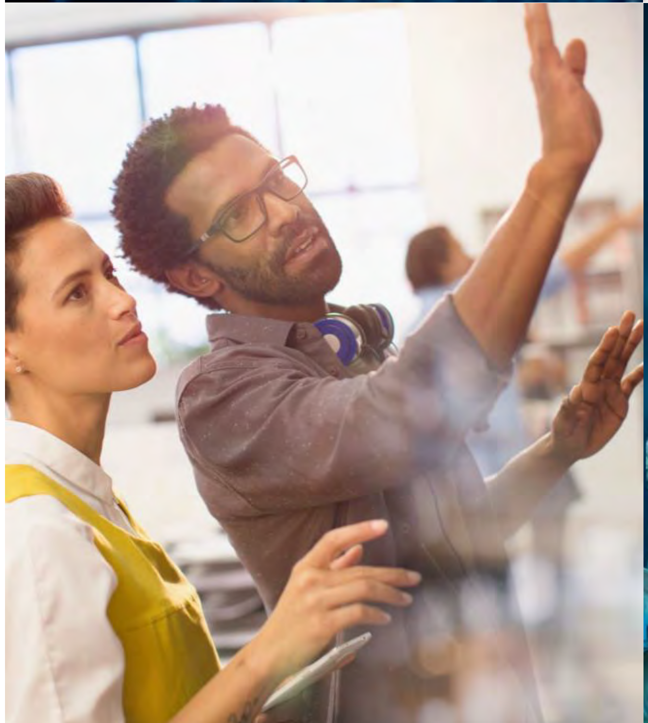
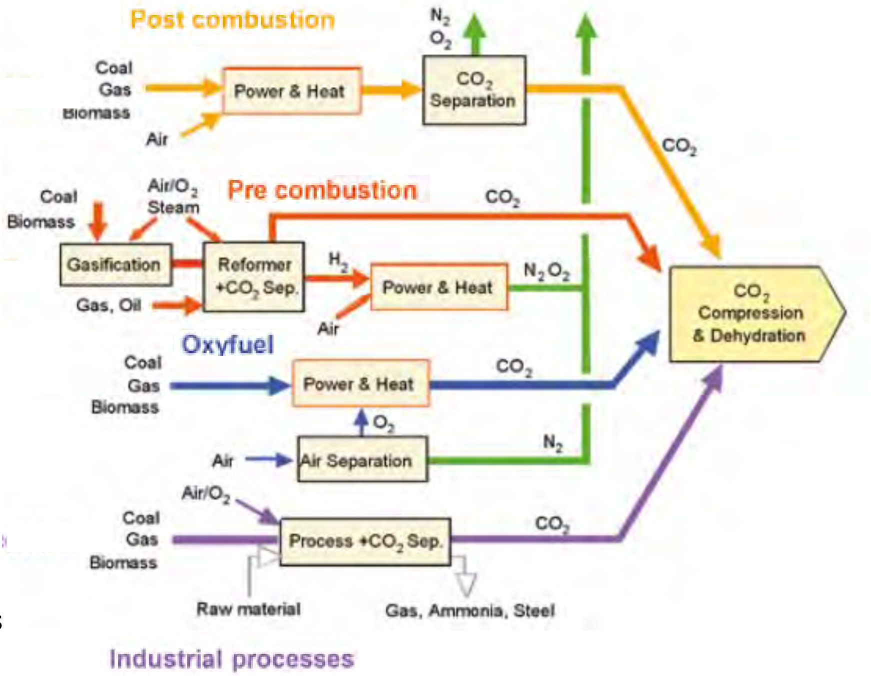


Capture costs include capital costs, operational costs and energy costs with 'current' technology costs driven largely by scale and purity of CO_2 stream

INTRODUCTION TO CAPTURE COST DRIVERS

- While they are a range of technological approaches being proposed for adding CO_2 capture to industrial sites to reduce site-based CO_2 emissions all leading approaches require:
  - a material capital investment to fund the new equipment to 'capture' the CO_2 and compress it to a suitable pressure for the chosen transport approach
  - increased operational and maintenance costs of the new equipment, and increased complexity in the operation of legacy assets
  - increased energy costs as:
    1. major capture approaches / compression are energy intensive themselves (for example heat energy required to regenerate amines; and / or
    2. capture processes require inputs that themselves are energy intensive to derive (e.g. pure O_2 for 'oxy-combustion' approaches)
- Looking across industries the scale of the capture/compression system (measures in t/annum) and CO_2 content (partial pressure) of the gas stream being captured are fundamental cost influencers for the 'current' capture cost across different industries:
  - Larger CO_2 streams will have lower per unit costs due to economies of scale – for example post-combustion capture costs halve when moving from 50,000tPA to a 500,000tPA system*
  - Higher partial pressure (i.e. higher CO_2 content in the gas stream) will lead to lower costs as it is easier to extract a unit of CO_2 from a high purity stream than a lower one. The extreme case is where a flue gas stream is high purity without additional treatment as in some industrial processes, so can be directly dehydrated and compressed.
- The level of contaminants and water content in the flue gas being captured can also be significant as purification and dehydration costs are also material
- Finally, note that site specific considerations including land cost, local labour cost etc. will also be a driver of cost difference in industries but across difference regions and locations



*James et al. 2019 – Capture costs level off significantly above 0.5-0.6MTPa, suggesting a GW scale gas power project would capture most scale economies

Cost reduction opportunities in capture are significant and can be driven further by falling financing costs

OPPORTUNITIES FOR CAPTURE COST REDUCTION

- While the chemistry of the capture of CO_2 is well known and demonstrated on a wide variety, the scale of application and optimisation to new industrial processes means that we are in 'cost discovery' phase for even the more mature carbon capture technologies and applications*.
- Good opportunities for bringing down per unit capex, opex (including energy) in the current generation of capture technologies comes from:
  - Economies of scale where the cost per unit of capture can be shown to decrease materially [mainly captured @1mtCO_2/yr scale]
  - Reduced redundancy and contingency – early projects will necessarily build in higher contingency and redundancy in e.g., spare parts to minimize failures and downtime;
  - Modularisation – i.e., as the technology becomes more common components that are currently bespoke can be provided by suppliers as standard products (so benefitting from economies of scale at the component supplier side)
  - Heat integration – the energy penalty can be materially reduced if 'spare' energy from combustion at the industrial site can be used rather than having to combust additional fossil fuels to create that heat
  - Process adaption –possible in certain industries that process itself can be amended to make carbon capture either integrated in the process or at least significantly easier e.g., using the Allam-Fedvedt cycle in power, or amending the calcination process in cement

KEY DRIVERS

- Due to the capital-intensive nature of capture, cost on a levelized basis will be significantly influenced by the weighted cost of the capital deployed. As such there are additional cost savings that to be gathered via **falling financing costs:**
  - Should arise from a reduction in technology/policy risk perception which should mean that there is a lower cost sources of capital are made available for the investment
  - Shortening project deployment timelines helps to decrease both interest during construction charges and lower risk perception (smaller time between capital deployed and operational revenues being earned)
  - At the extreme we see that a reduction in the Weighted Average Cost of Capital (WACC) from 15% to 3% could alone move the cost of a capture and compression in a gas power CCUS project from \$100/tCO_2 to \$55/tCO_2
- Continued R&D will enable next generation technologies to move on from the near-commercial pipeline (advanced chemical solvents, high CO_2 permeance membrane etc.) that could ultimately be more cost effective and efficient in capturing CO_2 (more effective capture of CO_2 from the flue gas, lower energy required for regeneration, higher degradation resistance)
  - The Technology Readiness level of a range of technologies is summarized in the following slide

Natural Gas Processing and compression may be an exception to this

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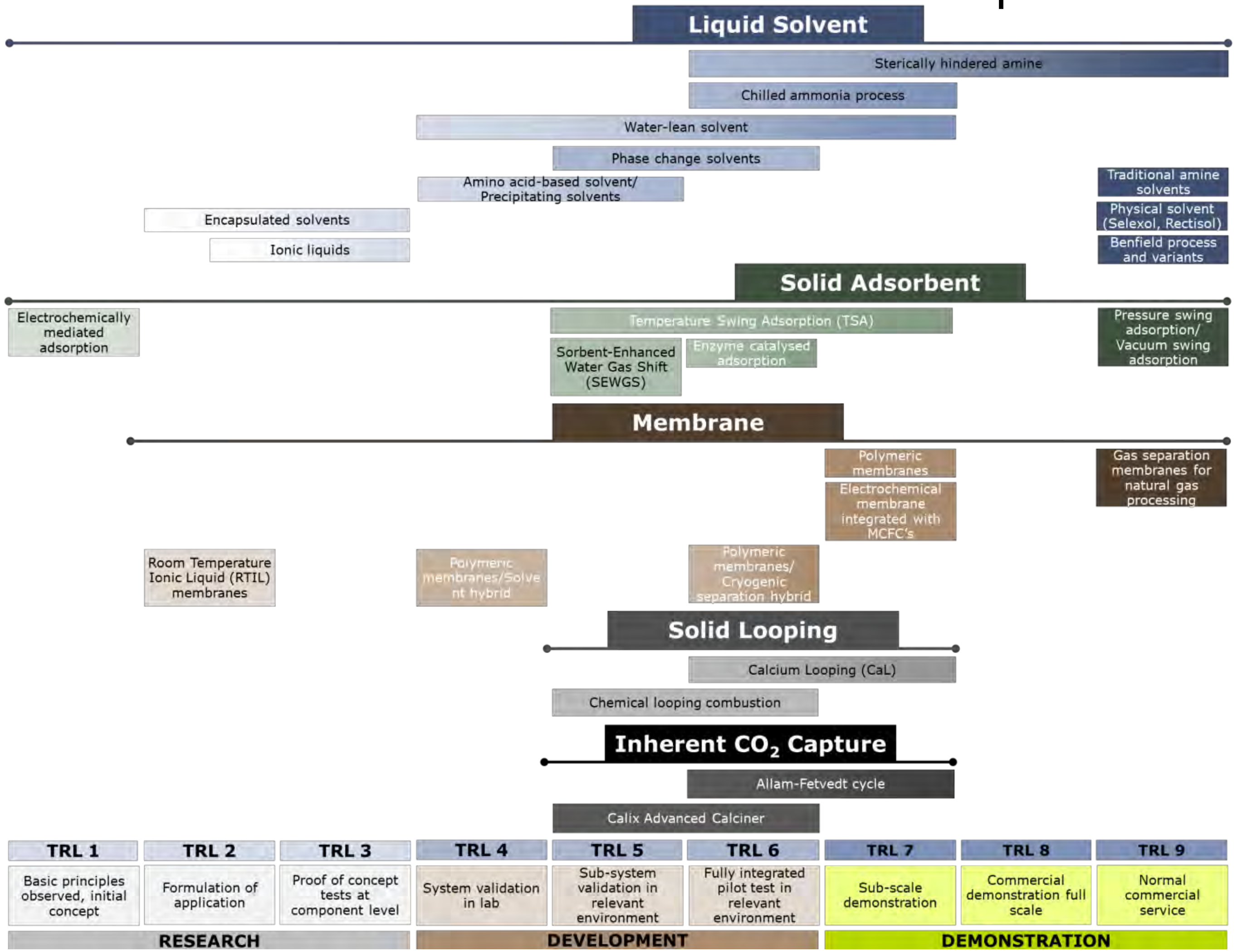
Limited amount of technologies in commercial operation, but many in demonstration and still more in development



The distance between Technology Readiness Levels (TRLs) is not a linear gap and some technologies will develop faster than others (with many technologies never progressing to TRL7 and above where they do not offer material benefits over more mature approaches)

In the near term capture dominated by Liquid Solvents and Solid Adsorbents which are used in the post combustion phase on flue gases – cost reduction still possible in 'mature' technologies

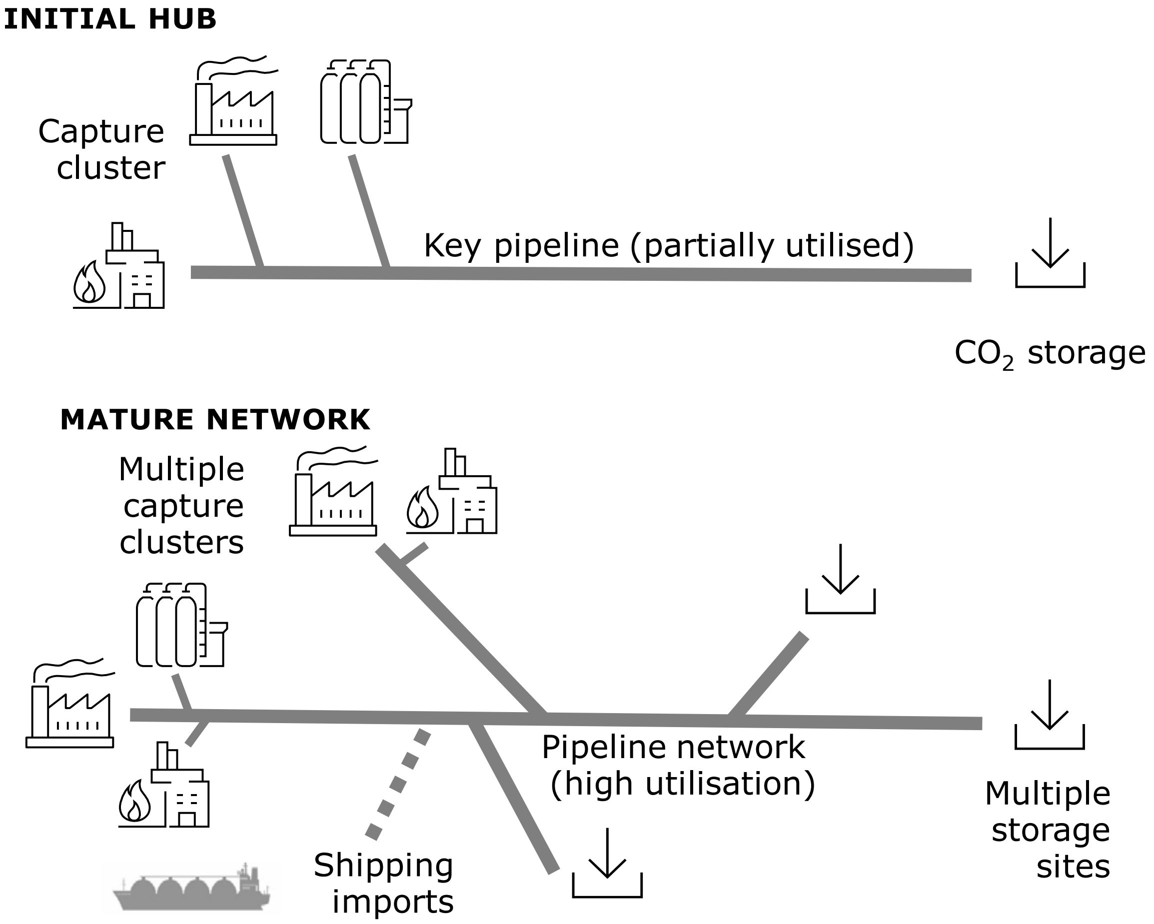
Membranes expected to evolve quickly driven by extensive research but are likely to be more costly in the short term

Solid Looping and Inherent CO_2 capture of large theoretical benefits over existing techniques, but are probably 3-5 year away from commercial demonstration, with additional time to enter commercial operation

T&S cost largely driven by distance and economies of scale as technologies are reasonably mature

FUNDAMENTAL T&S COST DRIVERS

- After CO_2 is captured and compressed and dehydrated, it then needs to be transported to the injection site, injected and monitored.
- Unlike capture where there is significant ongoing technical innovation and a variety of technical options applying across different industries, transport and storage solutions are largely based on mature technologies*, based on dealing with a relatively homogenous product.
- However, reported transport and storage costs are highly variable in the literature varying by a factor of 10. These differences in cost estimates are driven primarily by:
  - Transport distance (from capture to final storage)
  - Transport volumes
  - Transport option (pipeline vs shipping inc. need for interim storage)
  - CO_2 storage site characteristics (characterisation level, on/off-shore environment, capacity and injectivity)
  - Business model approach (direct funding of a hub vs trickle down model) pushing risk on different parties
- Rather than technology innovation (as technology steps largely mature) the main drivers for T&S cost declines come through:
  - Economies of scale [savings up to 20-30mtCO_2/yr scale]
  - Storage risk perception
  - Policy risk perception



*Exceptions include CO_2 transport via ship and certain monitoring and verification of CO_2 storage techniques which are relatively immature

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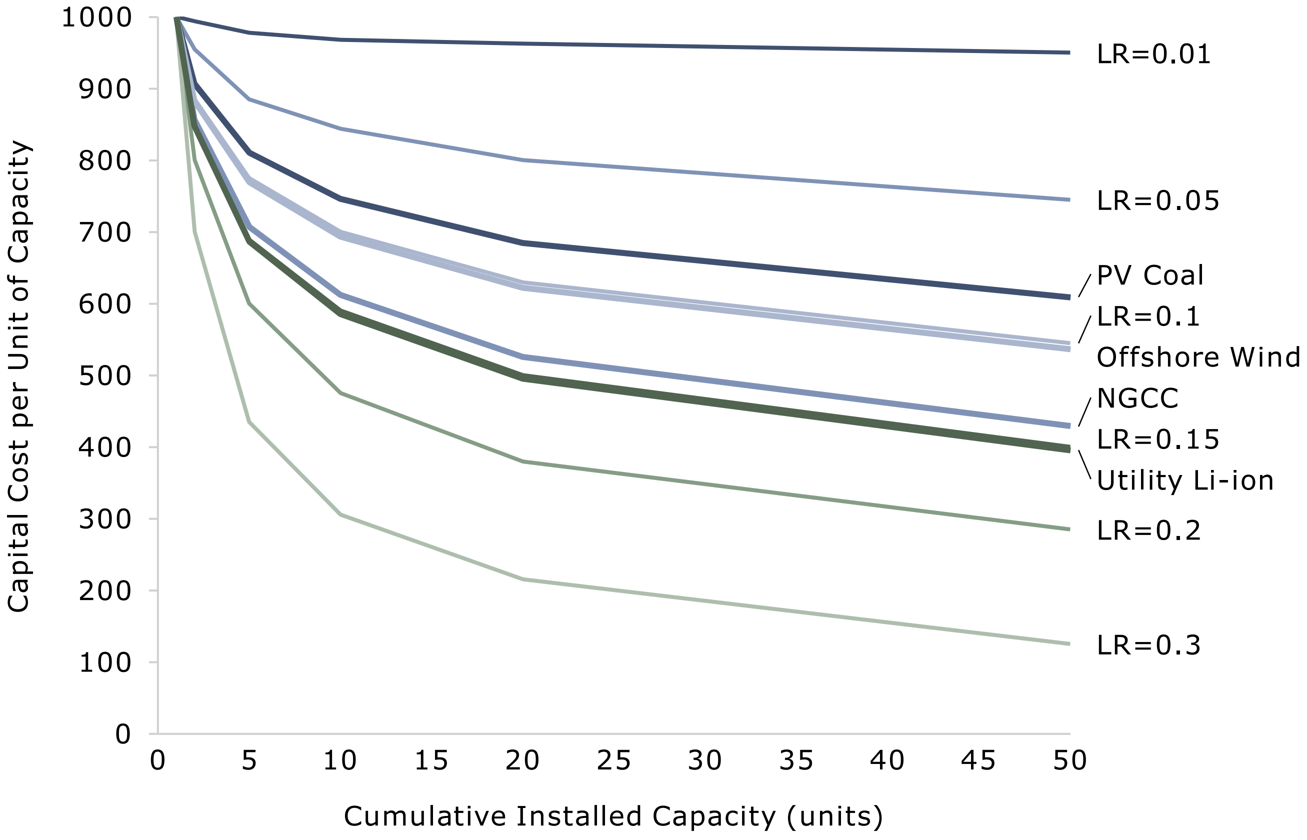
Cost-reduction model: estimating future costs using 'learning curves' factor in cost savings brought about through experience as capacity grows

ILLUSTRATIVE COST TRENDS FOR DIFFERENT LEARNING RATES



COMMENTS

- As illustrated here, these can vary significantly depending on the assumed rate of learning. Note on the chart that:
  - First unit of capacity here given arbitrary cost of 1000.
  - Learning rate, LR, can be defined as 'the fractional reduction in cost for a doubling of the initial capacity'. Shown here varying from 1-30%.
- For calibration, it is useful to base these rates on historical developments for similar technologies. However across industries we see a large range of learning rates:
  - <0% for nuclear-fired power – i.e. cost rising over time
  - 8.4% for Pulverised coal
  - 10.3% for offshore wind
  - 14.4% for Natural Gas Combined Cycle (NGCC)
  - 22% for solar PV
- To develop a cost curve for CCUS using this approach would require two key assumptions:
  1. The learning rate % – either based on historic learning rates for CCUS (where we have very limited capacity build to date) or selecting a technology or suite of technologies as good benchmarks for CCUS cost reduction; and
  2. The global volume roll-out of CCUS capacity over time

Source: Towards improved guidelines for cost evaluation of CCS, IEAGHG Technical Review 2021-TR05, August 2021

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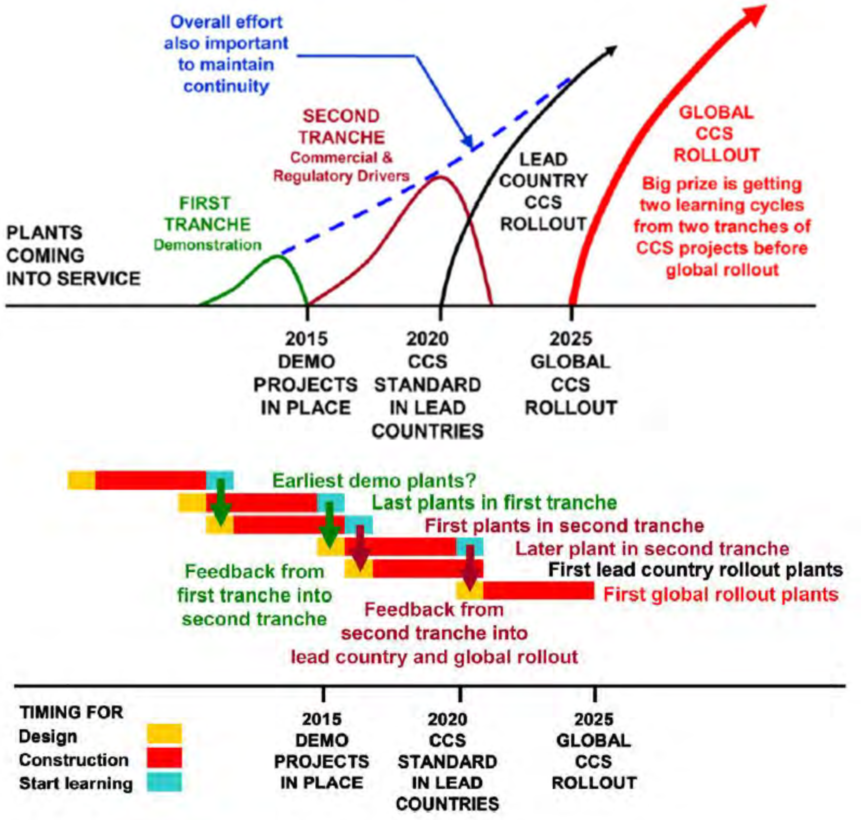
Cost-reduction model: generational learning cycles look at multiple project tranches/generations with learning feeding back into next generation

COMMENTARY

- The primary drivers for capture cost declines for 'current' capture technologies will be CCUS roll-out, which through successive generations of CCUS projects, will facilitate gains from:
  - Learning by doing – same technology but achieved cheaper. Boundary dam and Petra Nova (coal plant retrofits) both report they could have achieved 20% cost saving doing the same thing again
  - Scale up – first projects often sub-scale as governments, project developers and equipment suppliers all seek to limit absolute financial exposure
  - Reduced redundancy and contingency (design, maintenance, operation, financing lessons) – note that early sharing of this data allows others to benefit
  - Modularisation – as multiple projects move through roll-out we see equipment suppliers developing modular approaches which can significantly lower costs (20% cost saving for 2)
  - Heat integration – as confidence in approach grows, and speed of project deployment falls it makes more efficient heat integration
  - Better business models – as project succeed (or in some cases fail) we get a better understanding of what business models and contracting structures best allocate risk, thereby reducing levelised cost of new projects
- Can broadly be seen as a driving out of 'first-of-a-kind' cost penalties to reach a clear cost base for plants after ~10 years of scaling up the roll-out

COST REDUCTION THROUGH LEARNING CYCLES



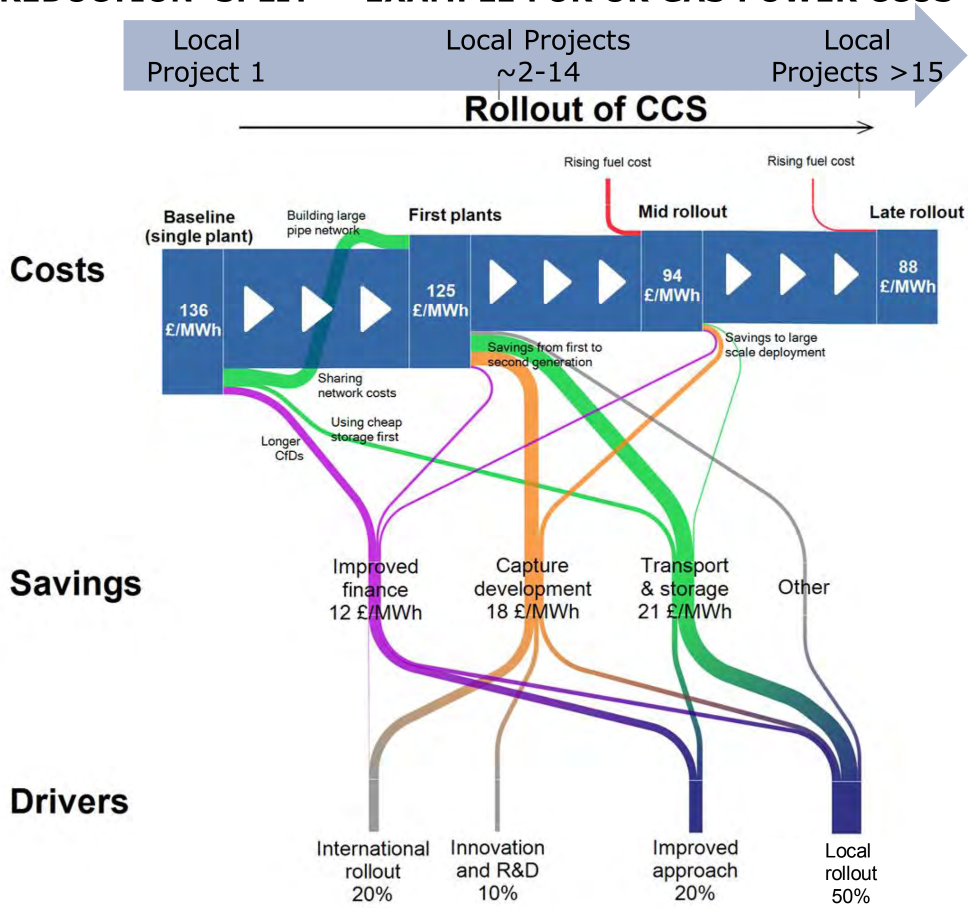
Preparing for global rollout, J.Gibbins, H.Chalmers, Energy Policy, 36, (2008), 501 – 507

Cost-reduction model: cost breakdown model using a levelized cost model to quantify how improvements in individual assumptions flow through

COST REDUCTION BREAKDOWN MODEL

- By building up a levelized cost model for CCUS projects, cost savings from successive generations of projects can be estimated and broken down into saving components /drivers
- Taking the example from Pöyry (AFRY) and Element Energy work for the UK Committee on Climate Change the cost saving areas were simplified into:
  - **Improved finance –** included savings from lower cost of capital, and reducing Interest During Construction costs
  - **Capture development** – included capex / opex / energy cost savings in the capture and compression stage
  - **Transport and storage** – savings arising from changes to the T&S system
- The saving areas can be thought of as having 4 broad drivers:
  - **Local roll-out** through creating CCUS hubs to lower T&S costs, lowering financing costs, providing confidence to scale up plant sizes [accounted for ~50% of cost savings]
  - **International roll-out** which leads to plant design improvements and cost savings in capture as well as some decrease in risk perception such that financial costs are lowered [20% of savings]
  - **Improved approach** which optimised business models which e.g. could develop lower cost storage sites [20% of savings]
  - **Innovation and R&D** which largely contribute by bringing forward new capture technologies (large degree of uncertainty but scope of work assumed no breakthrough technology) [10% of savings]

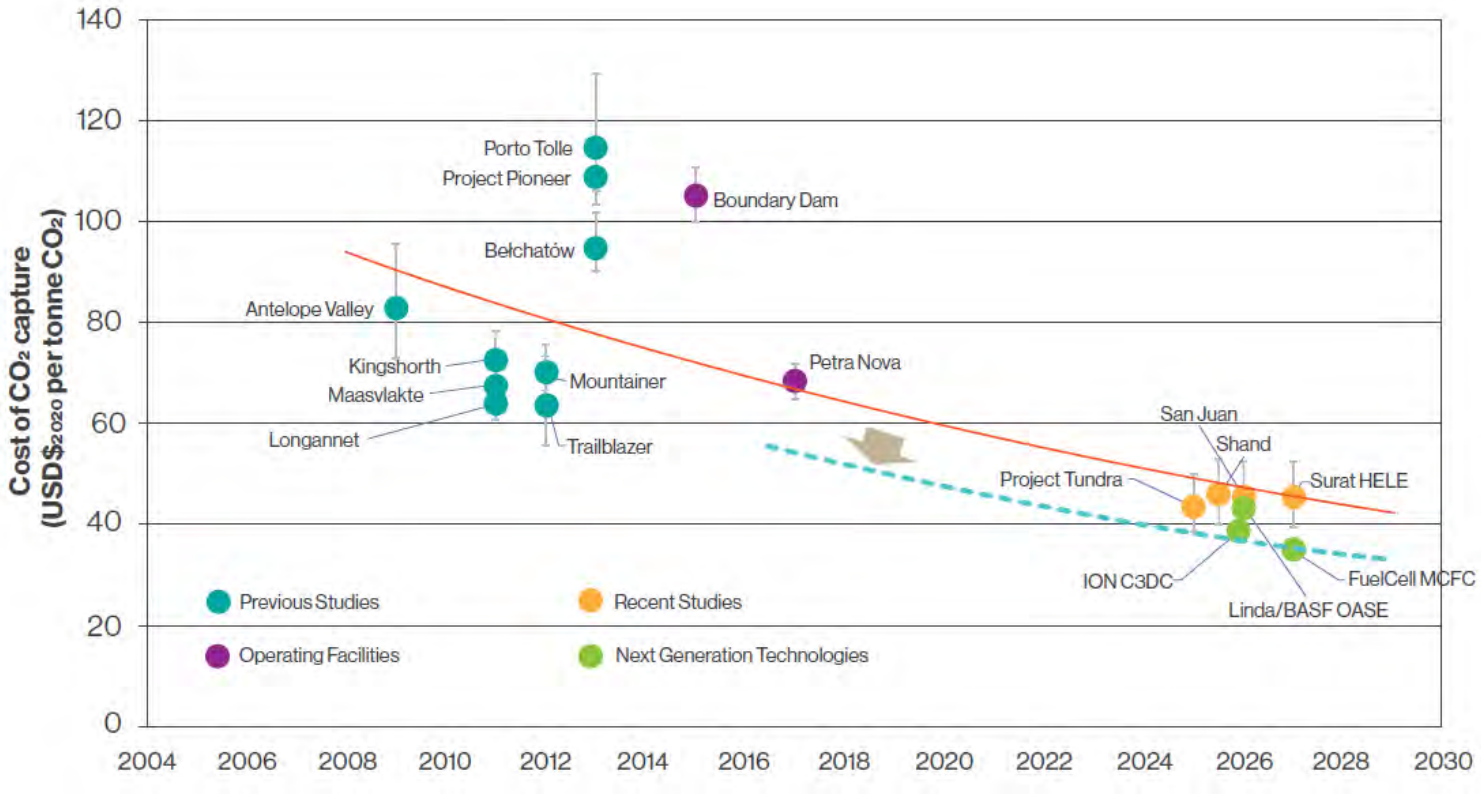
COST REDUCTION 'SPLIT' – EXAMPLE FOR UK GAS POWER CCUS



Adapted from Pöyry and Element Energy: Potential CCS cost reduction mechanisms for the Committee on Climate Change, 2015

Cost-reduction model: bottom-up engineering estimates for CCUS projects at different commissioning dates show drop out of 'first-of-a-kind' costs

CAPTURE COST LEARNING CURVE – EXAMPLE FOR COAL FIRED POWER PROJECTS



COMMENTARY

- Early projects for coal-power based CCUS had a capture cost between $60-120/tonne
- Learning rates have led to between 25-35% reduction in costs between FOAK and subsequent projects (for example Boundary Dam vs Petra Nova)
- Based on this trend capture costs would be around $40/tonne in 2030
- Recent studies and new technologies appear to be improving on that trend and the prediction is that these approaches could lead to a cost of $30-35/tonne, although it remains to be seen how quickly these new technologies can be brought to market
- As more projects are brought online in the late 2020's it will be important to confirm this trend and monitor where new approaches start on the cost curve
- Expected that cost reduction in the later 2030s will be much less rapid than in early years as we move into the later part of the technology development / learning curve with only incremental savings

Source: Evolution of CO_2 Capture Costs ('Next Gen' ION C3DC, Linde/BASF and Fuel Cell MCFC are claimed cost by technology developers) CCE 2021 (partly derived from GCCSI Technology Readiness and Costs publication)

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Global benchmarking for CCUS components show a wide range and some comparability issues but useful to evaluate own engineering cost data

INTRODUCTION

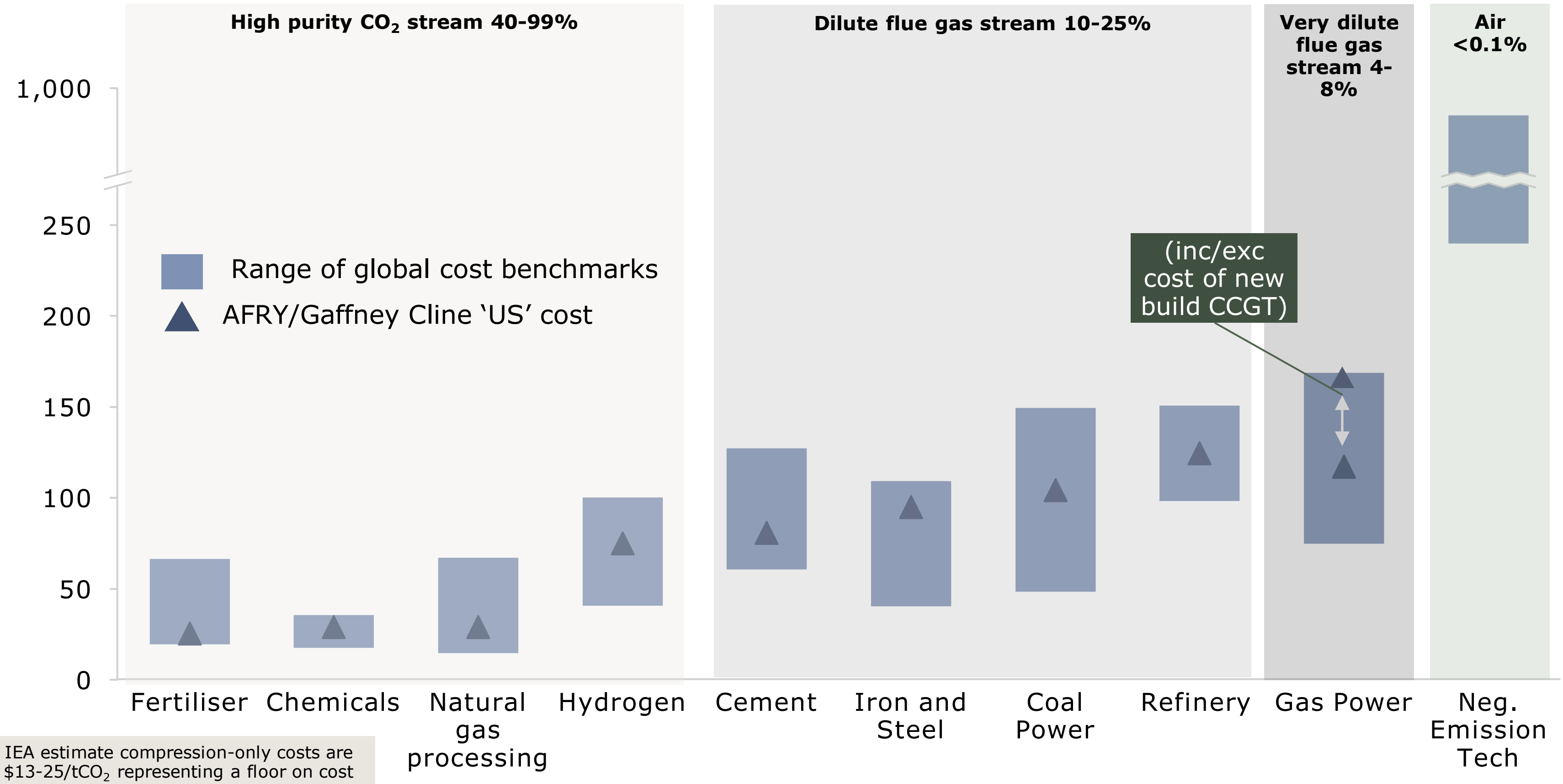
- Cost benchmarking for this work has been conducted based on a desktop review of a range of studies that have examined the current and future costs of CCUS over the past decade.
- Costs data for existing projects is relatively scarce – they are based on a small sample of 'full-scale' capture projects that have been commissioned and for which published costs are known including:
  - Boundary Dam coal-fired retrofit and Quest projects, Canada
  - Abu Dhabi Iron and Steel CCS project, UAE
  - Petranova, USA
  - Gorgon, Australia
- Most cost data therefore comes from engineering studies, either:
  - Feasibility or front-end engineering and design studies where detailed cost data for a particular project is produced in advance of a decision to proceed with investment - for example:
    - ROAD in the Netherlands
    - Peterhead CCS project and the Teesside Collective in the UK
  - more commonly, engineering firms have produced bottom up cost data for 'archetypal' or generic projects of a particular industry or type includes estimates from:
    - IEA
    - Global Carbon Capture and Storage Institute
    - Wood studies for BEIS,
    - Gassnova cost data for Norwegian full-scale CCS

CAVEATS

- Comparing overall capex / opex costs across industries is challenging for a number of reasons, not least because the assumptions that sit behind data are not always clear
- We have aimed to compare the data on a like-for-like basis where possible, but note that as ever a number of assumptions have been required so the resulting cost band is indicative rather than absolute
- Project scale in the studies tends to be very variable:
  - Coal or gas-fired power capture sites are typically for projects capturing volumes of 1-5mtCO_2 per annum
  - Estimates for chemical / fertiliser sites are typically in the 0.1-0.4mtCO_2 per annum
- Therefore to compare data across different industries on a consistent basis we express costs on a cost per tonne of CO_2 captured basis, using a real 2020 US dollar money base

Capture cost and compression cost benchmark summary shows large range across and within sectors – recent Gaffney Cline US studies match range well

'GLOBAL' CAPTURE + COMPRESSION COST BENCHMARKS (2020$/T$CO_2$)



IEA estimate compression-only costs are \$13-25/tCO_2 representing a floor on cost

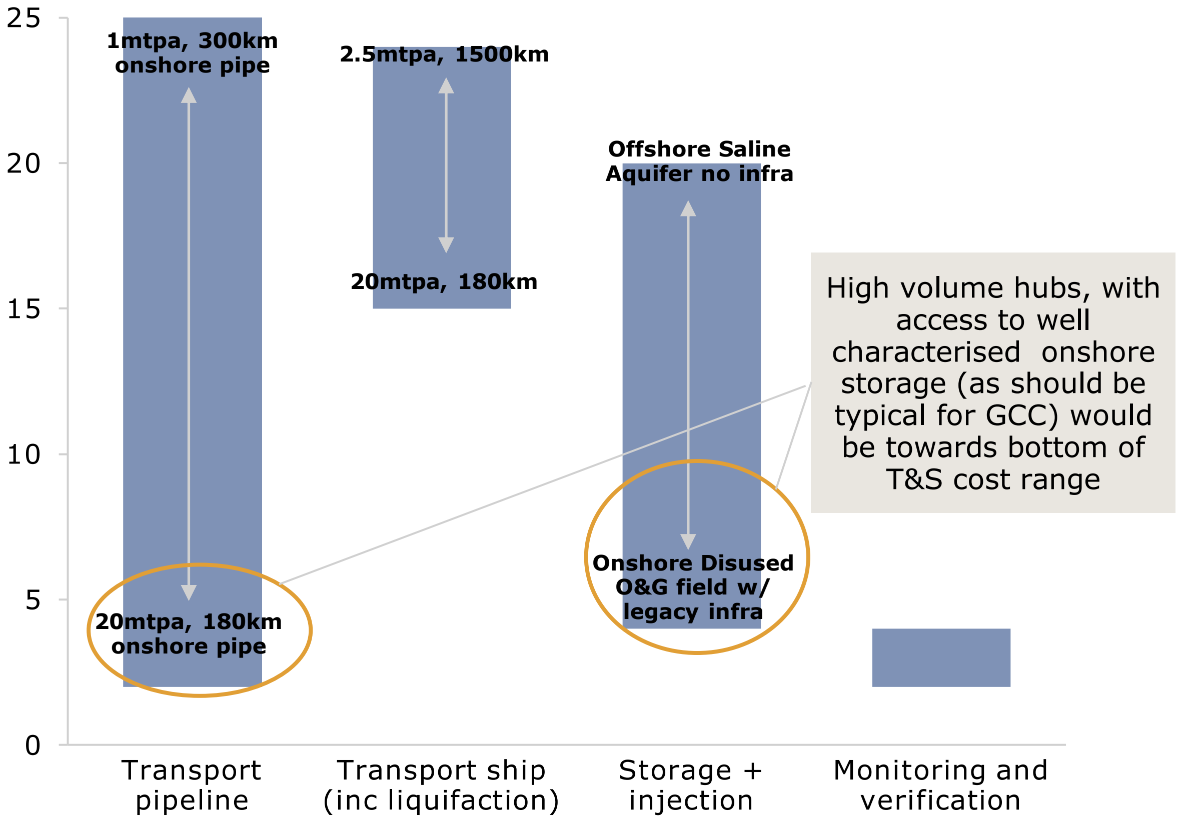
COMMENTS

- Global cost benchmarking shows a wide of capture + compression costs across most sectors – data points represent actual projects and studies for projects commissioning between 2020 and 2040.
- AFRY / 2019 Gaffney Cline cost figure based on work for the National Petroleum Council on potential US projects shows cost data that match well other sources in most sectors
- AFRY/Gaffney Cline data representative of cost for an at scale project in ~2030 without additional 'first-of-a-kind' (FOAK) costs
  - Costs are for 'at scale' project development
  - Costs represent a 'best available technology' for an average project (not just best site) so should be scalable for significant volumes
  - Costs relevant for US – so will need to be adjusted for GCC

Source: AFRY analysis of reported cost data (Boundary Dam, Petranova, Gorgon, Abu Dhabi, Illinois) and engineering estimates and studies from GCCSI, Imperial College, Clean Carbon, Wood, Shand, Teesside Collective, Gaffney Cline, IEA. Some outlier data-points have been removed, for example low load factor gas and power projects.

Transport and Storage cost benchmarks show a wide spread so development of hubs with good storage required to access the lower part of the range

GLOBAL' TRANSPORT AND STORAGE (T&S) COST BENCHMARKS (2020$/TCO$_2$)



COMMENTS

- On the Transport and storage costs are highly variable in the literature varying by a factor of ~10, driven primarily by:
  - Transport distance (from capture to storage)
  - Transport volumes
  - Transport option (pipeline vs shipping)
  - CO_2 storage site characteristics (characterisation level, volume, injectivity, legacy infrastructure)
  - Business model approach (direct funding of a hub vs trickle down model) pushing risk on different parties
- In reality expected that plants beyond the initial demonstration phases will target costs in the lower end of the spectrums shown, by selecting sizing and location choices
  - Development of hubs should keep transport costs for pipelines low, if storage sites are available relatively close to capture and if these are well utilized (i.e., 20Mtpa)
  - On the storage side sites will be selected that are low cost from being well characterized, having good access (e.g., onshore), and with good injectivity. If large volumes of high purity CO_2 are available, we would expect overall storage costs to be minimized:
    - Recent Gaffney Cline report for the National Petroleum Council in the US shows expectation of ample CO_2 storage available in the US for <$10/tCO$_2$

Adapted from GCCSI March 2021, Technology Readiness and Costs Of CCS, based on 30-year asset life and using data from National Petroleum Council (US, 2019) and Zero Emissions Platform (2013 through 2019, various

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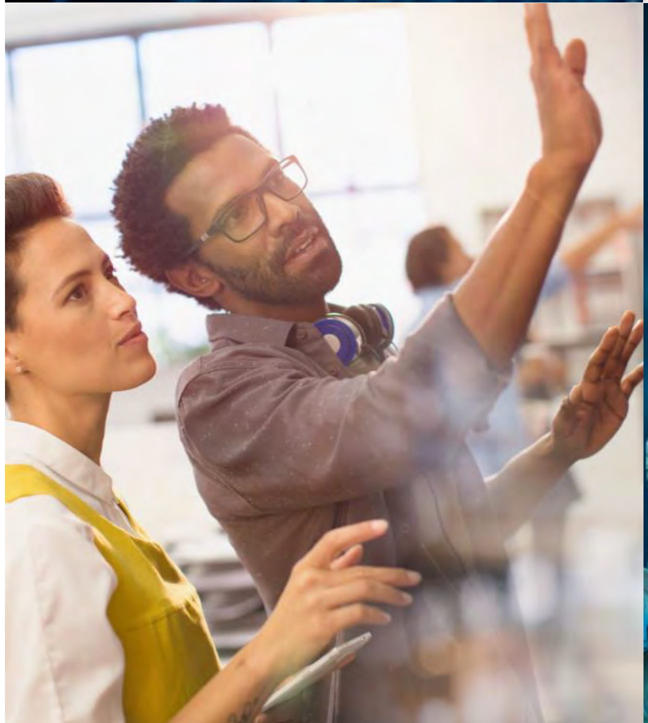

CCUS costs in GCC estimated to be lower cost than our international benchmark prices based on recent experience with large industrial projects

OVERVIEW: OUTLOOK FOR CCUS COSTS IN THE GCC

- Overall good reasons to expect that overall CCUS could be relatively low cost in the GCC region as it rolls-out:
  1. History of deployment for renewable generation in the GCC shows the ability to achieve world leading prices in low carbon (renewable) technologies:
     - Relatively low land cost
     - Relatively low labour costs
     - Business model attractive to investors – stable long-term payment structure (other markets have more merchant risks)
  2. Storage is relatively well characterised (although noting that oil and gas sites as stores will typically be better characterised than aquifers), significantly onshore and with some likely potential for reuse of legacy assets (pipeline routes, injection sites etc)
  3. Significant local skill-set in sub-surface management and engineering that can be re-deployed from the oil and gas sectors
  4. The volumes of CO_2 available to capture at key hubs is large enabling rapid capture of economies of scale
  5. Strong possibility to pair CCUS with emerging markets for hydrogen/ammonia, low carbon products and direct air capture
- However, we do expect some barriers to the rapid roll-out of low cost CCUS such as the lack of existing policy framework in the GCC around e.g. CO_2 emissions capping, CO_2 pricing and CO_2 storage can be expected to act as a initial deployment barrier compared to other global markets with more advanced frameworks (in e.g. US and Europe)

TRANSLATING US/EUROPEAN COSTS TO GCC EQUIVALENTS

- Utilised AFRY experience from >10 years of developing power projects in European / US markets and GCC countries
- Based on AFRY internal database of large project costs in GCC we estimate savings vs a US gulf coast levelized capture cost assumptions in 5 main areas:

Cost saving relative to US gulf coast		Comments
Capex	-20%	Based on experience with thermal + renewable power projects due to low/no development risk and lower cost land
Hurdle rate	-3%	Long-term attractive contracts (government bearing materially more risk) and low cost local finance
Opex	-30%	Economy of scale from large project size, no business rates, no grid costs, lower cost labour
Interest During Construction %	-3%	Construct of low-cost lending + less environmental restrictions impacting build time
Energy cost	0%	Nat gas ~$3-4/MMBtu in both markets – notable that this is <50% of typical cost in Europe

- Transport and storage likely to also benefit from lower capex costs in GCC relative to the US – notable that both regions should be able to benefit from large economies of scale in T&S due to the large capturable emissions set

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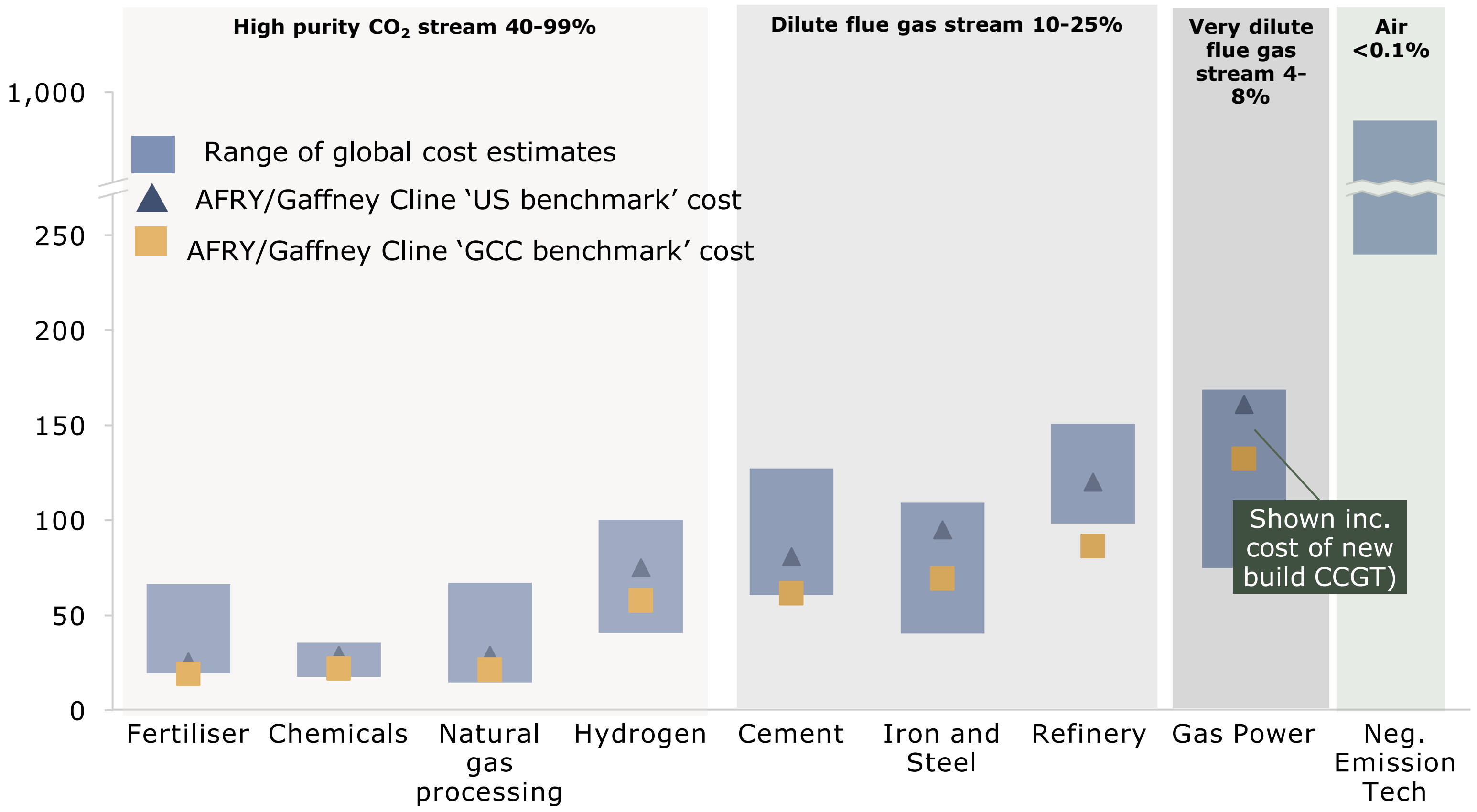
Adding GCC benchmark cost data shows potential capture cost advantage over US east cost benchmark – most notable in more dilute streams

GCC CAPTURE + COMPRESSION COST VS GLOBAL BENCHMARKS (2020$/TCO$_2$)



COMMENTARY

- Adjusting costs to represent a benchmark for capture in the GCC shows the advantage deriving from the relative cost advantages of the GCC
- Note that these do not derive from technology advantages but from economies of scale, lower operational costs (e.g. labour and business rates) and a potential advantages in finance
- Fertiliser, Chemicals, Natural gas processing all show similar cost levels (<$20/tCO$_2$ captured) as the overall capital and operational costs of these technologies are low
- Cost advantage most notable in more dilute CO_2 streams where capital and operational costs are higher overall
- Overall cost advantage for GCC calculated as ~15-25% of costs compared to benchmark US projects

Source: AFRY analysis of reported cost data (Boundary Dam, Petranova, Gorgon, Abu Dhabi, Illinois) and engineering estimates and studies from GCCSI, Imperial College, Clean Carbon, Wood, Shand, Teesside Collective, Gaffney Cline, IEA)

AFRY approach uses a hybrid of learning rate model to describe capture evolution over time and a generational model to define T&S evolution

LEARNING RATE MODEL DESCRIPTION

- A differential approach to cost reduction if applied for:
  - Capture and compression costs
    - significant opportunity for reduction in capex, opex and energy penalty reduction through the development of new capture technologies in particular
    - Significant opportunity for declining financing costs in the early years as risk perception is normalised
    - After we move through initial 'cost discovery' and simple learning-by-doing phase (likely roughly by 2030) the process of cost reduction characterised by assumed learning rate
    - Given the uncertainty of global CCUS roll-out rate (in terms of rate of doubling of capacity) we have simplified the assumption as a rate of decline per year
  - Transport and storage costs
    - business model assumed to 'separate' the T&S component opportunity to allow for low initial financing costs for transport and storage
    - Network modelled as a transport and storage network which gets filled over time – as the network fills the average per user cost then lowers for that 'network'
    - Once a network is 'full' an additional 20-30mt transport and storage facilities is added, which is then filled etc

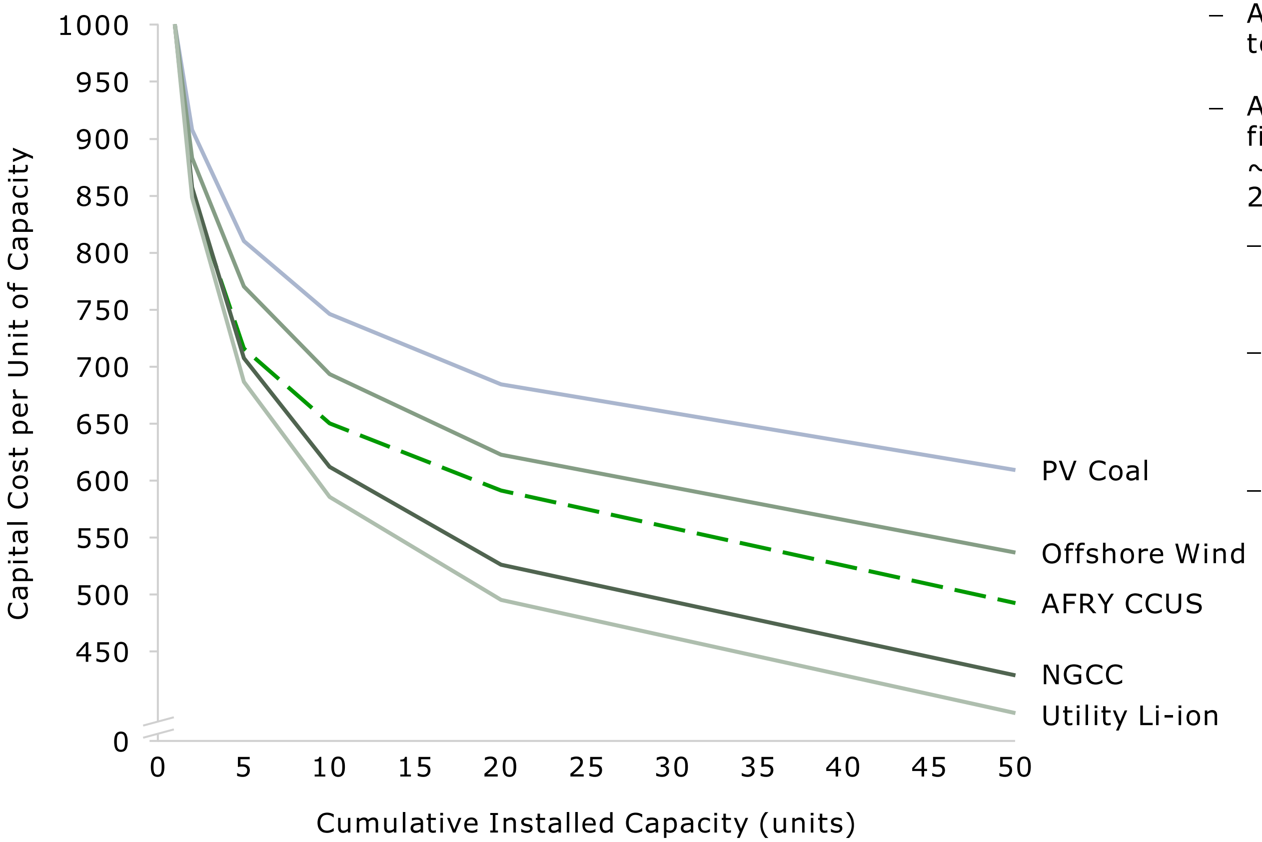
LEARNING RATE MODEL COMPONENTS

Capture and compression	– CAPEX learning rate – rate at which the $/tCO$_2$ capital costs of capture and compression falls over time – Energy cost/penalty learning rate – rate at which the % energy penalty/cost falls over time – OPEX learning rate – rate at which non-fuel, non-T&S opex falls over time – Improvements in 'hurdle rate' – rate at which the % Weighted Average Cost of Capital (WACC) or hurdle rate for capture/compression capex falls over time
Transport and storage	– Scale – size of transport and storage network installed, which then needs to be filled up over time – Utilisation – amount of overall pipeline and injection capacity used – CAPEX Learning rate – rate at which the $/tCO$_2$/year capital cost of new transport and storage facilities falls over time*

*T&S learning rate assumed at zero in current projections, based on gradual cost reductions being balanced out by the need for more distant or technically challenging storage facilities over time

Resulting approach to cost reduction shows a capture cost reduction profile that sits between that observed for Pulverised (PV) coal and NGCC

LEARNING RATE COST TRENDS BY TECHNOLOGY



COMMENTS

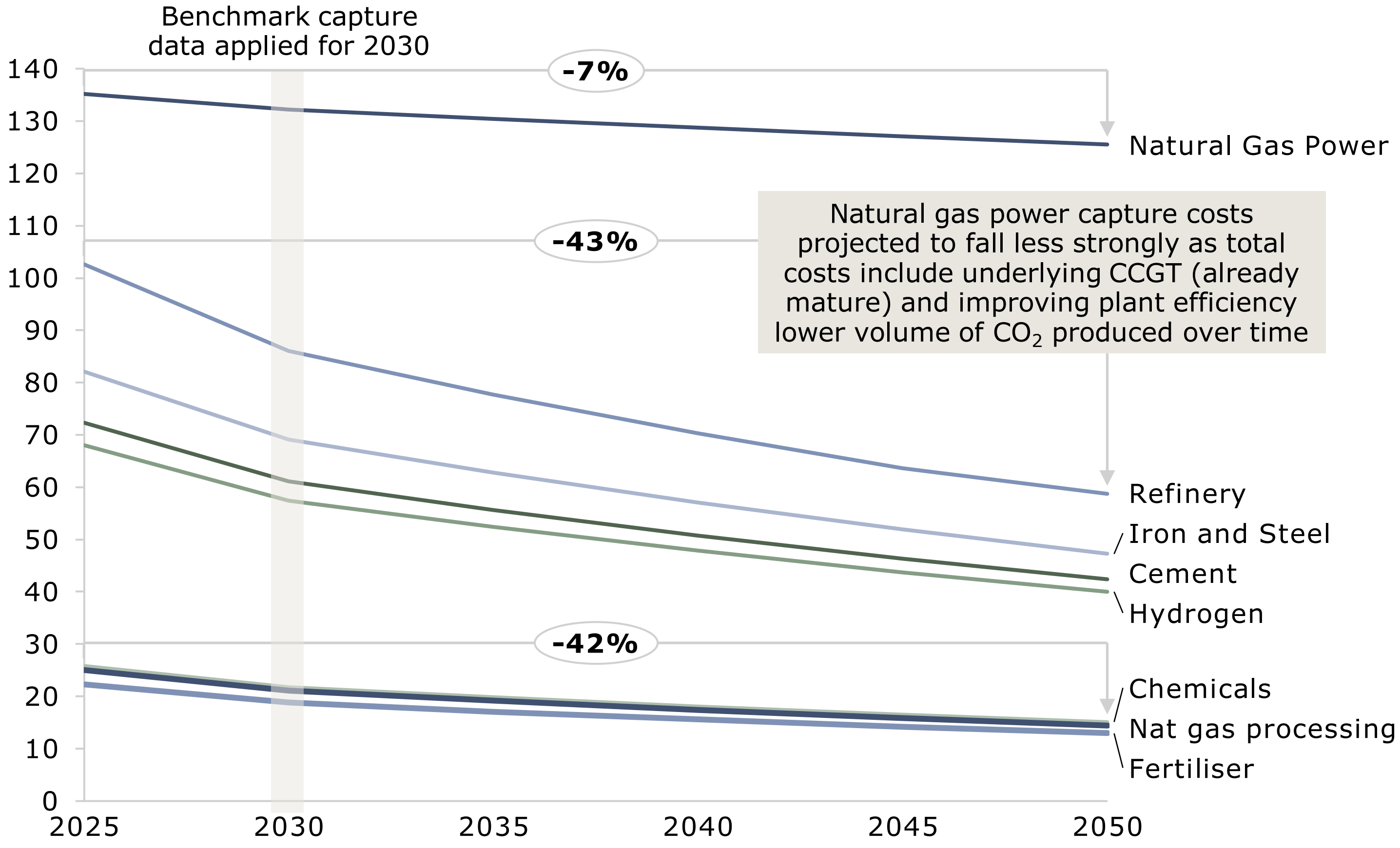
- AFRY approach to cost reduction shown in the chart with comparison to the learning rate benchmarks
- AFRY cost reduction assumptions are based on engineering data for first-of-a-kind projects (FOAK) and Nth-of-a-kind (NOAK) projects by ~2030, with an annual learning then assumed for the period beyond 2030.
  - Capture cost evolution to 2030 shows rapid cost declines as FOAK premiums are driven out of system. Data to 2030 based on observed project cost reductions and engineering studies.
  - Post-2030 assumptions for long-term learning rates are based on a range of comparable technologies learning rates* – equating to achieving cost savings at approx. half the annual rate compared to the pre-2030 period
  - AFRY's resulting CCUS cost curve applied for GCC capture

Learning rate (% y-t-y)	FOAK to NOAK (pre-2030)	post-NOAK (post-2030)	Basis
CAPEX	3%	1.9%	Pre-2030 - engineering data Post 2030 - benchmark learning rate
Opex	3%	1.9%	
Energy penalty/cost	3%	1.29%	AFRY assumption based on engineering studies for CCC and UK Cost Reduction Task Force
Hurdle rate	1.40%	0.80%	

*Source: Towards improved guidelines for cost evaluation of CCS, IEAGHG Technical Review 2021-TR05, August 2021
AFRY CCUS curve shown as industry average (exc power) an example, assuming by 2025 we have gone through 1 doubling of capacity (i.e. 2x), thereafter reaching 5x in 2030, 10x in 2035, 50x in 2050

Resulting GCC capture evolution for industry show a fall of ~30% for most industries – natural gas power has smaller falls due to underlying CCGT cost

GCC CAPTURE + COMPRESSION COST EVOLUTION (2020$/TCO$_2$)

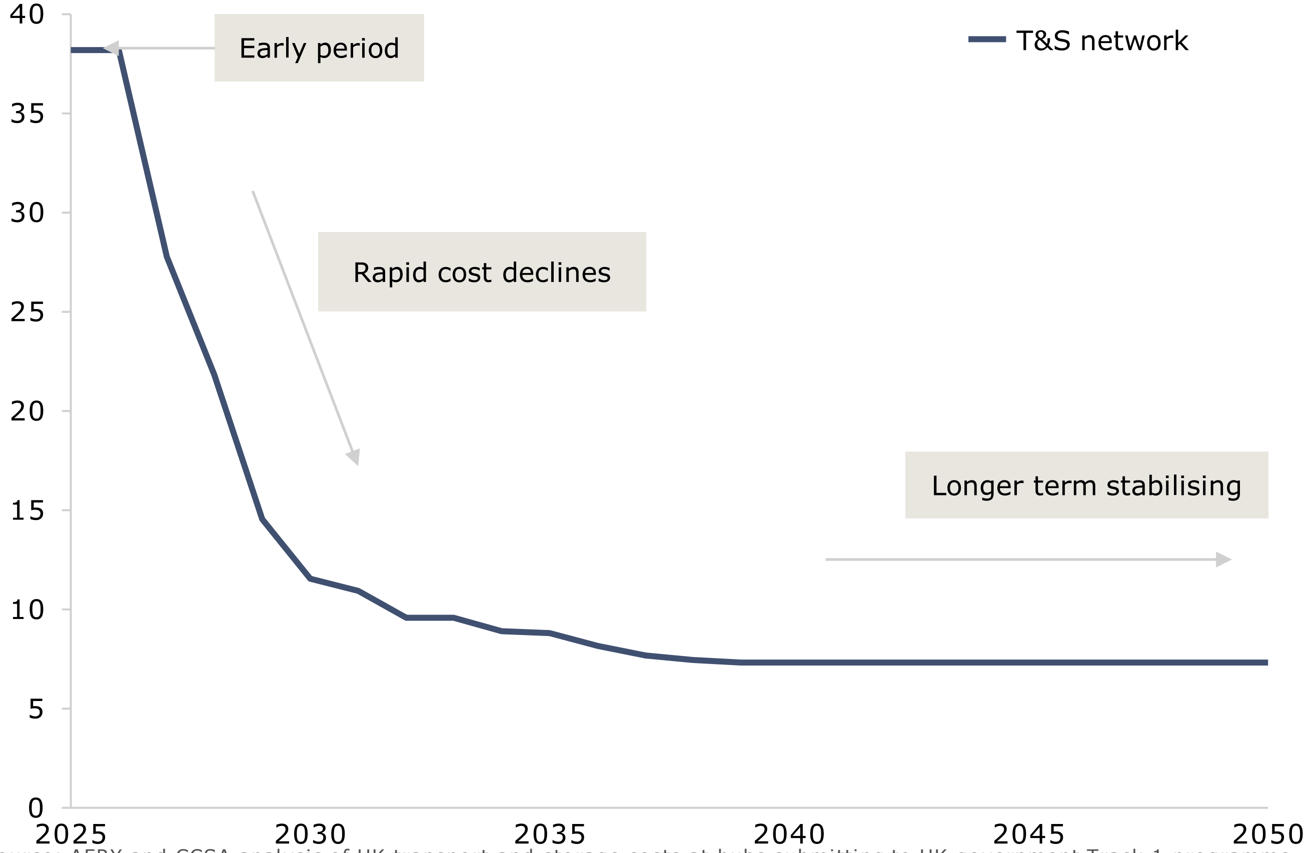


COMMENTARY

- Capture cost evolution to 2030 show rapid cost declines as new generations of projects benefit directly from cost discovery and learning from previous generations
  - Significant first-of-a-kind expected to be drive out of the system over next decade
- Beyond 2030 cost decline slows as cost savings become more incremental – based on learning rates of a range of technologies which have shown rapid industrial uptake in the last 30 years
- Refineries benefit the most in absolute terms as capture costs per tonne of CO_2 fall from >\$100/tCO_2 in 2025 to ~\$60/tCO_2 in 2050
- Chemicals, natural gas processing and fertiliser production all start with capture costs at \$20-30 /tCO_2 and fall to less 20/tCO_2 by 2050
- Natural gas power costs projected to fall less strongly overall as:
  - the baseline cost includes the cost of installing the CCGT which is already a mature technology; and
  - As plant efficiency improves the volume of CO_2 produced per MWh also falls

Evolution of transport and storage costs in GCC can be expected to be internationally competitive and decline with major economies of scale

TARGET EVOLUTION OF T&S COSTS IN THE GCC REGION (REAL 2020 TCO_2 CAPTURED)



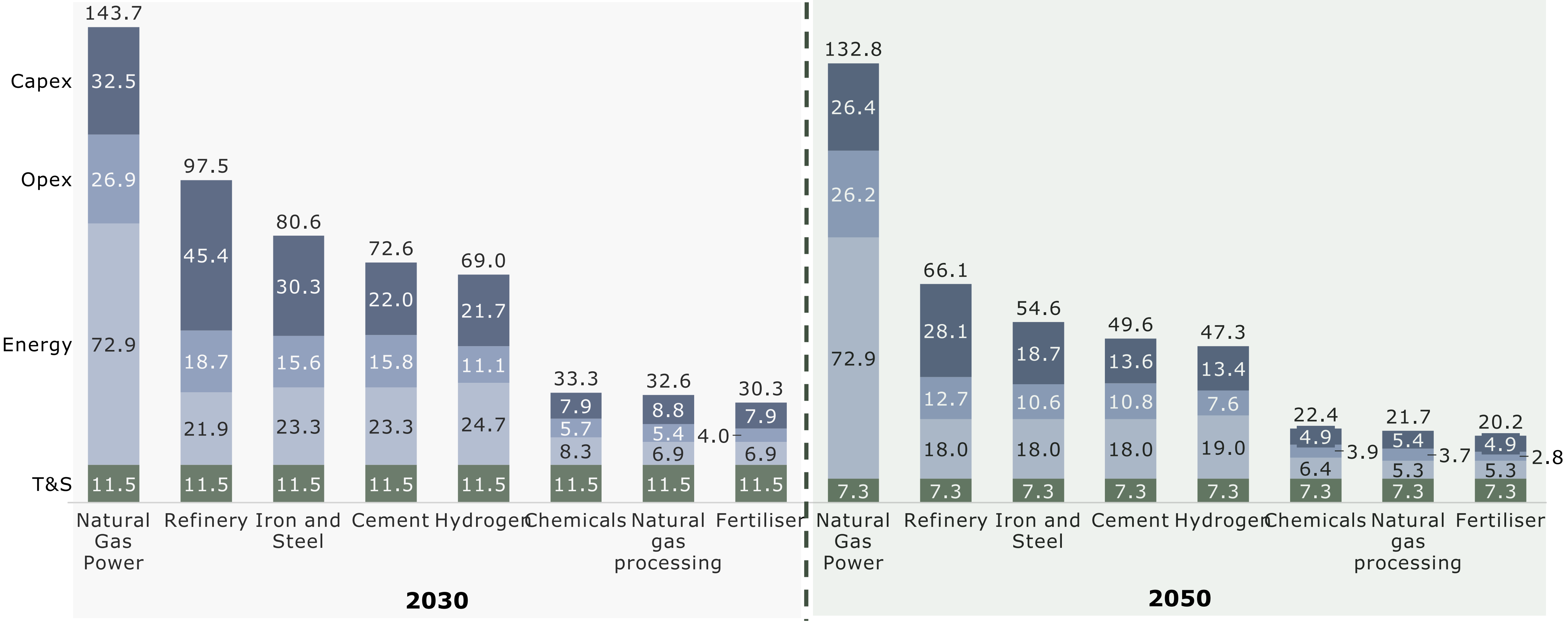
Source: AFRY and CCSA analysis of UK transport and storage costs at hubs submitting to UK government Track 1 programme, adjusted for lower GCC capex and at scale / utilisation levels corresponding to IEA Sustainable Development Scenario (i.e. reaching 80mtCO"/y by 2035 – see Workstream 1)

COMMENTS ON ASSUMED T&S EVOLUTION

- Early period
  - Early costs >$30/tCO_2$ for a medium sized network with relatively low utilisation – approx. 1-5mt CO_2. Likely that both EOR and first permanent saline storage sites developed
- Near/Mid-term
  - Rapid cost declines as first T&S hubs are filled out and further transport and storage networks are developed, costs fall to around $10-15/t$CO_2$
  - Over time, the economies of scale of usage result in $/t$CO_2$ cost savings even with a large network, if usage will be sufficient
- Mid-/Long term
  - Network expands, with multiple large regional hubs developed (20-30MtCO_2 per annum+) with large dedicated storage networks now commonplace – costs trend towards lowest end of T&S estimates (<$10/t$CO_2$)
- Once a full-scale multi-hub network costs are assume to stabilise
  - Although some learning may take place which could lower capex/opex costs, this is assumed to be counterbalanced by the need to gradually develop more distant or harder to access storage sites

Levelised cost modelling for benchmark CCUS projects in the GCC across a range of relevant industries – cost savings derive in all cost areas

LEVELISED COST BREAKDOWN BY INDUSTRY (REAL 2020 $/TCO$_2$ CAPTURED)



CHAPTER 8

Hydrogen

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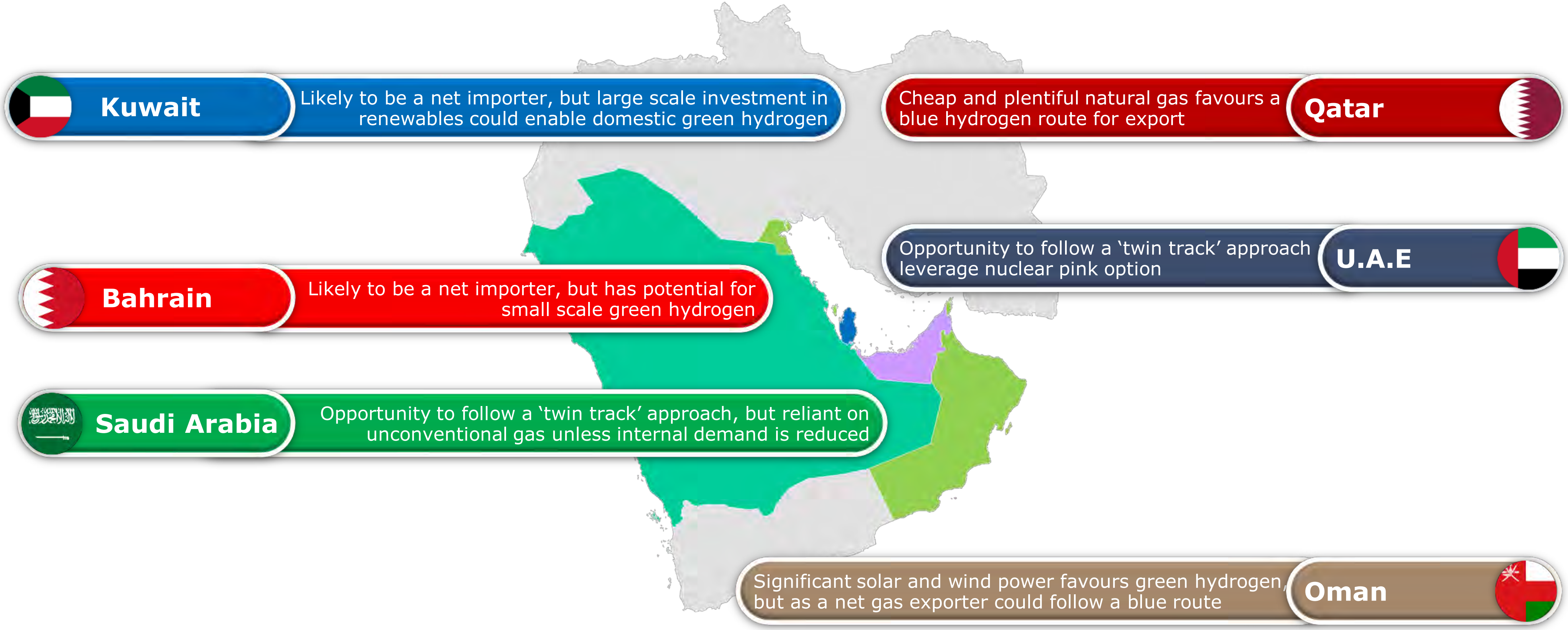
The GCC is well placed to follow a twin track approach to hydrogen development but the opportunity is not split evenly across states



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8. Hydrogen

No easy solution – green needs massive renewables expansion, blue needs storage, turquoise and red need further investment and research

Colour		Process	Description	Key advantages	Key challenges
White		None	Naturally occurring hydrogen, limited to volcanic vents and limited geological situations	Zero emissions, high purity hydrogen in native form that simply requires harvesting	Difficult to identify
Green	**optimise**	Electrolysis	Electrolysis is an existing technology (small-scale use) that splits water into hydrogen and oxygen using electricity. Hydrogen produced can only be considered zero carbon if the electricity used is itself zero carbon	No direct carbon emissions and no other by-products that need to be stored	Higher cost, questions about scalability
Pink			Same as electrolysis but instead of renewable electricity using nuclear energy	Low direct carbon emissions, ability to use waste heat in the process	Higher cost, public acceptance of nuclear
Blue		SMR/ATR with CCS	As below but in order to be ‘blue’ (carbon-neutral), it needs to be combined with Carbon Capture and Storage (CCS) of the CO_2 produced.	Currently the most developed option, especially at scale and as such presents the most cost effective form of hydrogen production even with the addition of CCS	Complex storage of CO_2 gas. Political opposition to CCS in many countries
Turquoise	**Research**	Pyrolysis	Pyrolysis is the decomposition of methane into hydrogen and solid carbon. A developing technology, it has the potential to play an important role in hydrogen production in the future. Residual carbon is in solid rather than a gaseous form	No complex CO_2 storage in underground caverns as in the case with CCS. Solid carbon can be used in existing industries, such as carbon black for tyres, in concrete for construction, or new uses such as graphene	Early stages of technology development
Red		In-situ oxidation	Oxygen is pumped into a subsurface accumulation of hydrocarbons and ignited. The resulting reaction produces hydrogen which is then selectively produced to surface via palladium membranes which leaves carbon and other contaminants in the ground	Would be zero-emissions and make use of depleted oil and gas fields	Technology yet to be proven commercially and still at pilot stage
Grey	**Eliminate**	SMR/ATR	Steam Methane Reforming (SMR) is a thermal process already used today. Reacts methane (CH4) with steam to produce hydrogen and CO_2. Auto Thermal Reforming (ATR) is a similar process but uses oxygen, CH_4 and CO_2 to produce syngas	Currently most widely used form of hydrogen generation and usually an integrated part of plants and refineries	Most common form of production currently, Significant emissions of CO_2
Black		Partial oxidation	Usually heavy crude oil is heated and reacted with oxygen and steam to form hydrogen	Makes use of heavier and less useful crude fractions	Significant emissions and contaminants released
Brown		Gasification	Coal or lignite is heated at 700°C (without combustion) and oxygen and/or water vapour is added. The mix of carbon monoxide (CO) and water vapour is transformed into carbon dioxide (CO_2) and hydrogen.	Syngas is a more efficient combustion material and can be used to generate synthetic fuels as well as hydrogen	Dirtiest form of hydrogen production, syngas requires further treatment to be utilised

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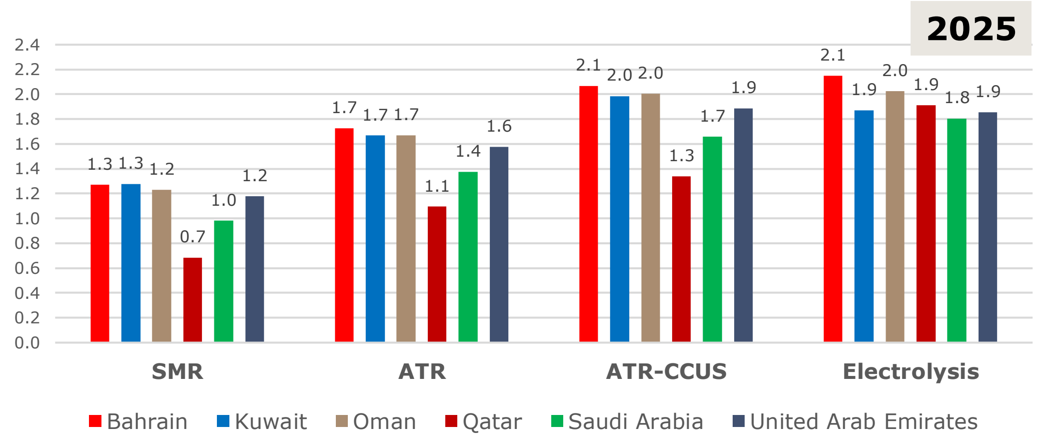
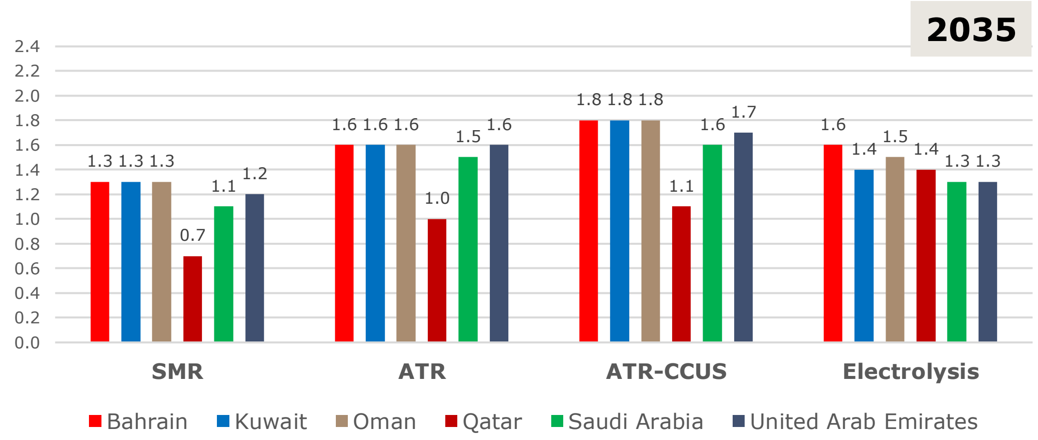
For the long-term green hydrogen offers the best opportunity across the GCC, but a twin track approach is recommended

COMMENTARY

- By 2025 costs for green hydrogen are at parity with blue for Bahrain, Kuwait, Oman and the United Arab Emirates
- These costs reduce still further by 2035 which challenges the economics of large-scale investments in blue hydrogen in those states
- Blue hydrogen costs for Saudi Arabia and Qatar are lower than for green but only Qatar maintains this cost advantage by 2035
- Blue hydrogen costs in Qatar are already cost competitive with grey hydrogen production in the other GCC states
- Further investment in renewable generation capacity in the GCC region will prepare member states to meet their sustainability targets and to become pivotal players in the green hydrogen market

LEVELISED COST OF HYDROGEN - $/KG,H2



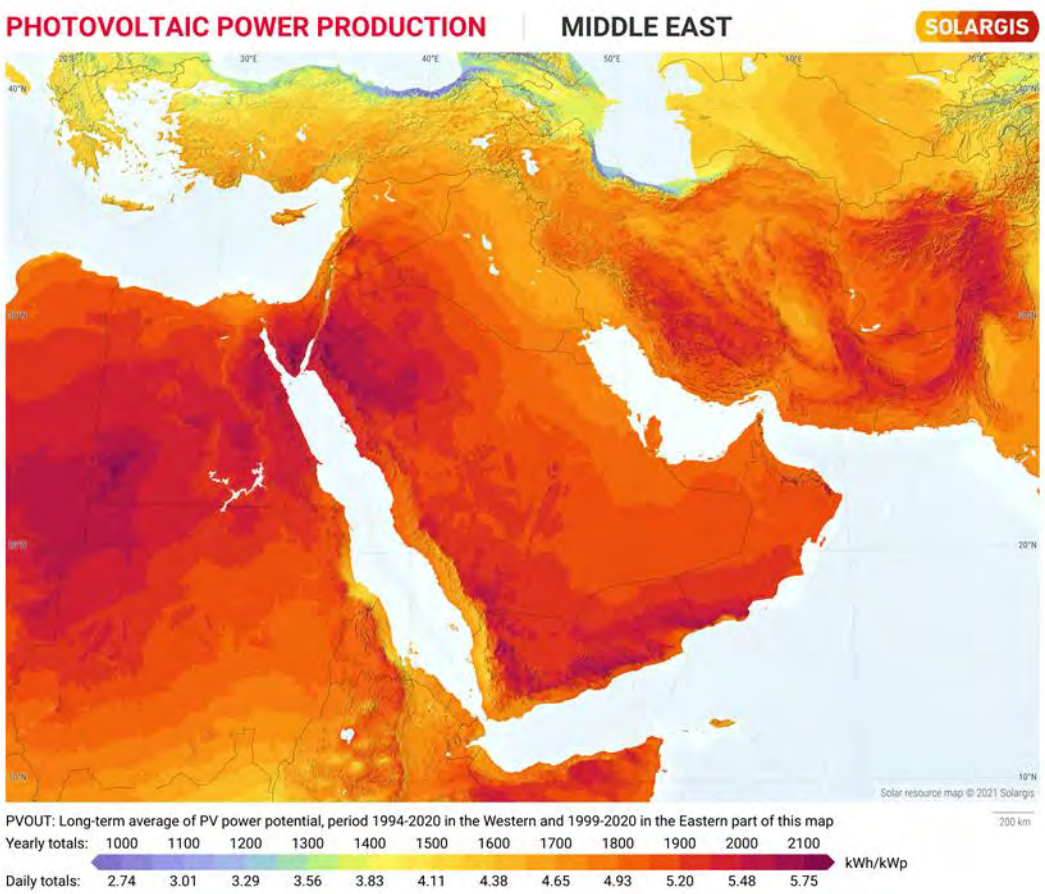


SMR-CCUS not shown as greater efficiency and ease of capture for ATR means any new plants will be ATR based (90% VS 60% capture rate)

Solar resources in the GCC are world class and would support extensive green hydrogen production

Shegaya, Kuwait

ACWA Project, Saudi Arabia

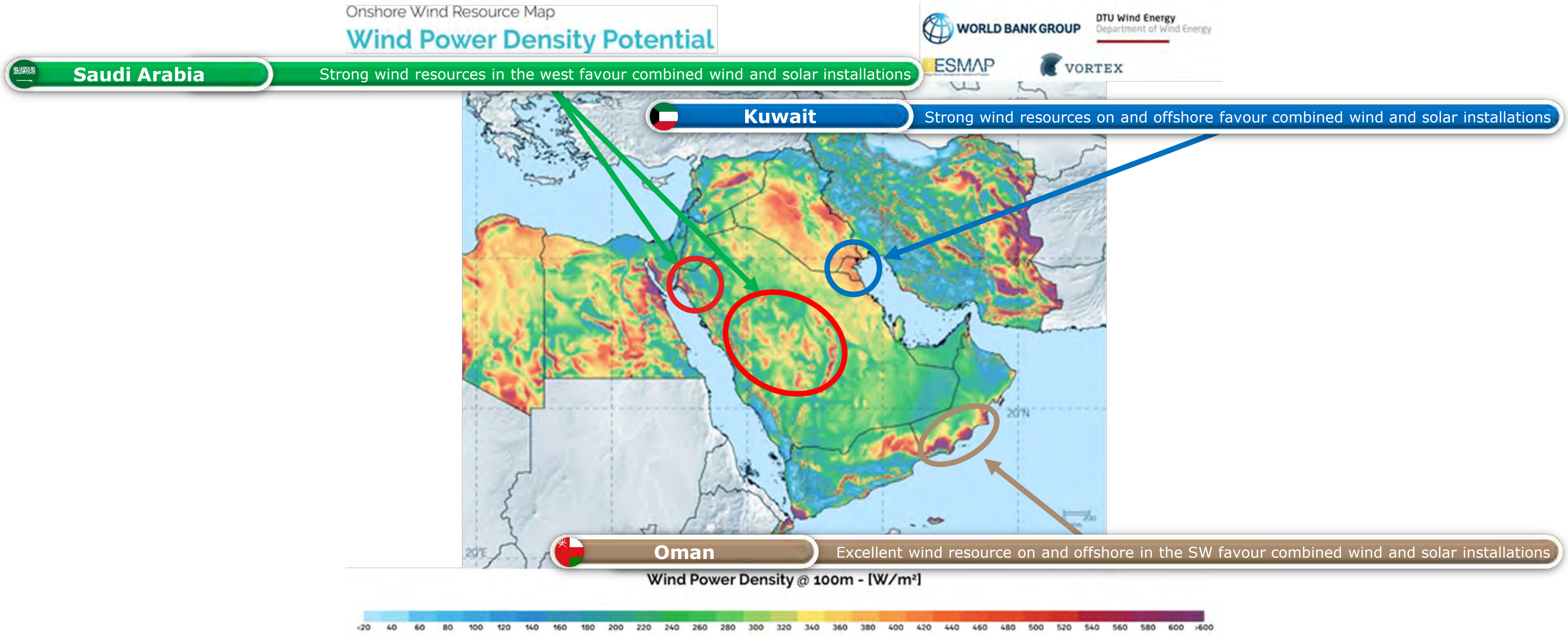


Al Dhafra, UAE

Mannah, Oman

ACWA Plant pictured is in Morocco as current plant under construction

Oman also enjoys world class wind resources, but other GCC states can also benefit from combined green hydrogen production



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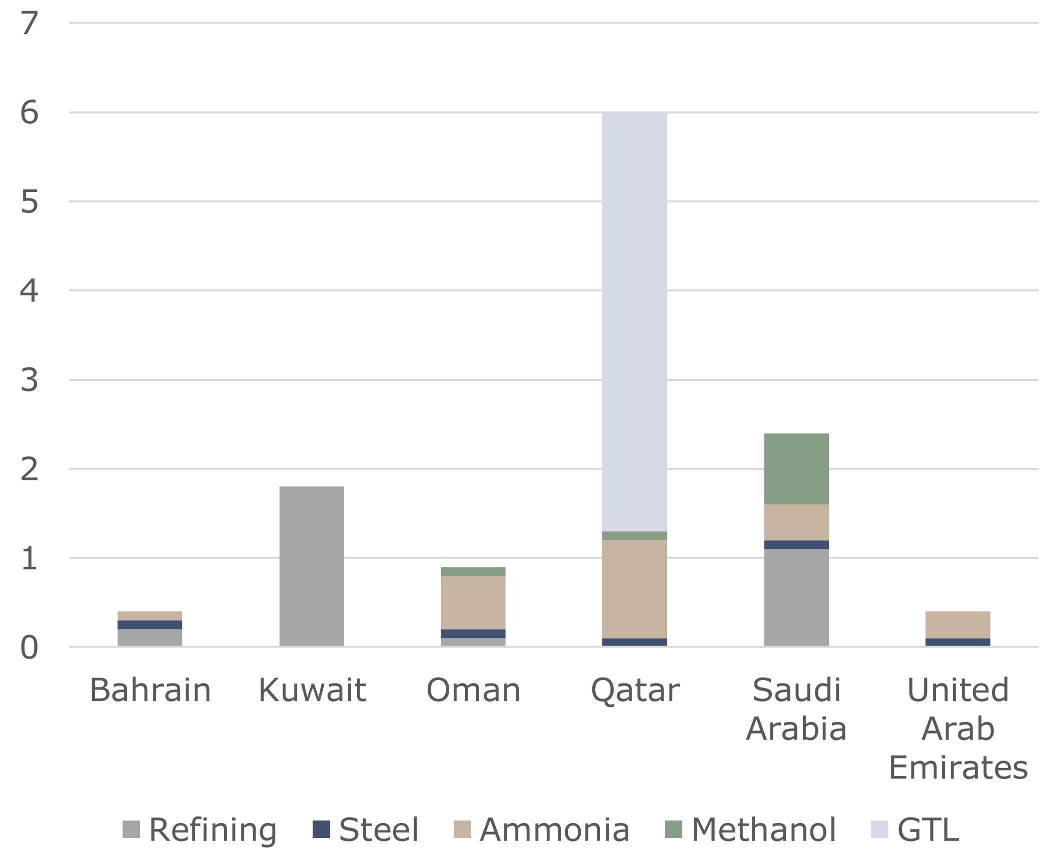
The GCC domestic hydrogen market is projected to grow to 25-50 Mtpa by 2050 driven by growth in the industrial sector

DESCRIPTION

- GCC countries consumed circa 12 million tonnes of grey hydrogen in 2019. The entire quantity was produced by on-site production units at oil refineries, petrochemical plants, steel manufacturing facilities, and Gas-to-Liquid (GTL) plants. Oil refining, chemicals, and GTL (only in Qatar) are considered to be the heaviest hydrogen consuming sectors in the GCC region
- In 2020, grey hydrogen consumption in oil refineries grew to 4 million tonnes, while 1.5 million tonnes were consumed in steel production, and 5 million tonnes in the chemical industry
- Future hydrogen consumption in the GCC market is projected to grow to 25-50 million tonnes per annum by 2050 driven by the growth of the industrial sector
- Saudi Arabia, Qatar, Oman, and the United Arab Emirates are expected to pioneer low-carbon hydrogen production in the GCC region due to the abundance of cheap natural gas resources, hydrogen planning at the respective ministries, and formidable domestic and international partnerships to support the uptake of hydrogen at a commercial scale
- Bahrain and Kuwait could potentially become hydrogen importers to decarbonise local oil refining and aluminium industries

GCC HYDROGEN DEMAND (MTPA) - 2019



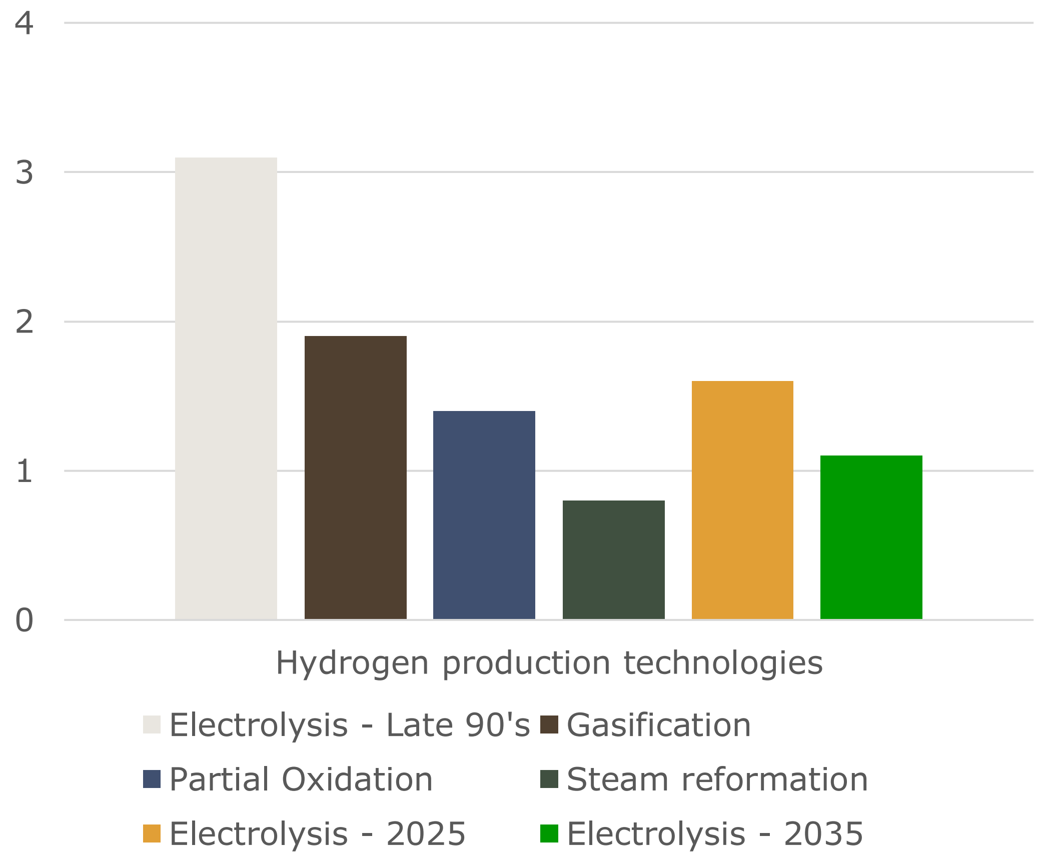
Source: IEA, Qamar Energy, Dii Desert, GTL in Qatar refers to wider natural gas value chain industries such as GTL and LNG

Despite the abundance of oil in the GCC region, partial oxidation must be carefully compared to other hydrogen production technologies

COMMENTARY

- SMR vs. POX – feedstock cost
- Learning curve for POX
- Key cost components:
  - Cost of feedstock
  - Lifting cost
- The opportunity cost of using oil for hydrogen production as opposed to selling it on the international market
- The indications are that in the short term oil to hydrogen makes little sense, but longer term if that oil has a value of zero and production cost is low it may work economically
- In this scenario the total cost would have to compete with what is expected to be large scale cheap green hydrogen and established blue hydrogen

INDICATIVE AVERAGE PRODUCTION COST COMPARISON ($/KG,H2)

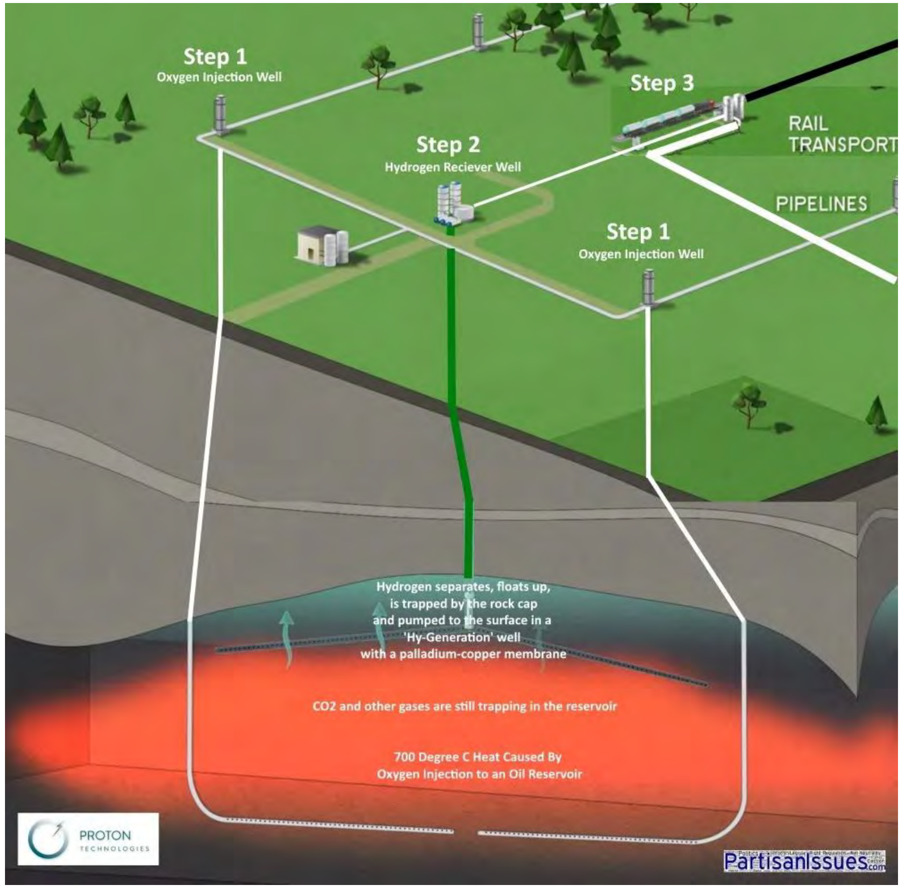


Red hydrogen offers a promising low cost route for oil to hydrogen, but existing processes are likely to be lower value than selling oil directly

A COLLECTION OF PROVEN STEPS COMBINED IN A NEW WAY

- Red hydrogen is produced using a technique called ‘fire flooding’ which is an in-situ oxidation reaction
- The process is proven and has been used in industry for secondary and tertiary recovery (e.g. Marguerite Lake Field)
- In this process oxygen is pumped into the reservoir containing the oil and ignited, at temperatures above 500°C, injected steam or existing water vapour reacts with the hydrocarbons to produce syngas
- Adding extra water to the syngas creates a reaction that produces CO_2 and more hydrogen
- The CO_2 and other impurities would remain underground as hydrogen is produced through selective membranes
- The challenge is getting the temperature to 500°C and under control and proving the membrane in the subsurface
- Most oilfields have at least 50% of reserves remaining at the end of field life which leaves huge scope for deployment

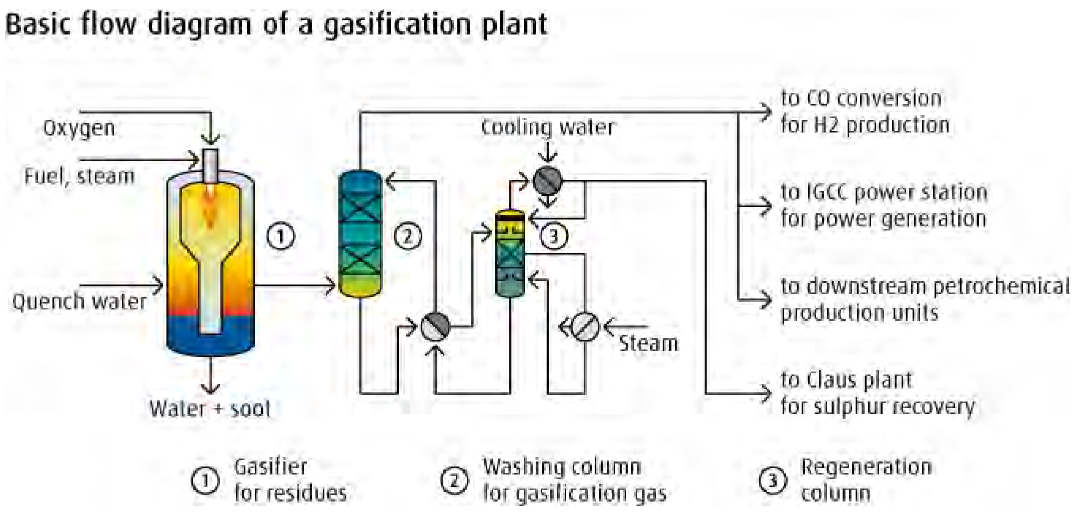
HYGIENIC EARTH ENERGY (RED HYDROGEN) PROCESS



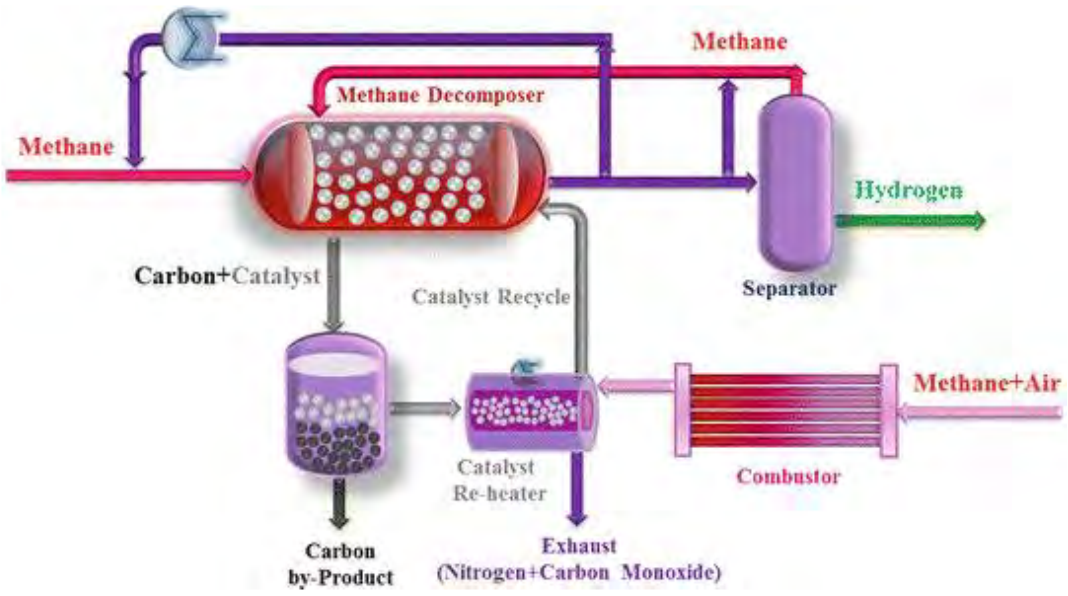
Source: Proton Technologies

In the absence of red hydrogen oil to hydrogen can be obtained via POX, an additional hydrocarbon route is available through pyrolysis

PARTIAL OXIDATION REACTOR SCHEMATIC



METHANE PYROLYSIS REACTOR SCHEMATIC



Partial oxidation is generally used for heavy fuel oils, given the low value of these products compared to lighter fractions, but all can produce hydrogen

- Partial oxidation (POX) is ideal for obtaining hydrogen from heavy fuel oil
- POX and gasification processes are identical and the terms used interchangeably. There are several gasification plants using heavy oil residues and liquid fuels in Saudi Arabia, USA, Italy and Spain. Generally, POX is used when gaseous (methane) or liquid (heavy fuel) is the feedstock while gasification is the term used when solid feedstocks such as coal or biomass are required. Handling solid feedstocks and the residue ash that results makes the gasification process more complex and adds significantly to the capital cost
- In POX, oxygen is fed at a level below that which is needed for complete oxidation and produces hydrogen and carbon monoxide (syngas)
- When processing liquid feedstocks like oil, a small amount of residual carbon remains (0.5-1% by mass) which is necessary to sequester ash from the reactor. The three reforming technologies compare as follows:

Technology	Advantages	Disadvantages
Steam reforming	Most industrially applied process, no oxygen required, lowest process temperature, and optimum H2/CO ratio for H2 production	High GHG emissions
Auto-thermal reforming	Low process temperature and low methane slip	Limited experience, requires air or oxygen
Partial oxidation	Decreased desulfurization requirement, no catalyst required at high temperatures, and low methane slip	Low H2/CO ratio (depends on the length of the hydrocarbon), very high processing temperatures, soot formation/handling makes the process more complex

- New technology development including ceramic membrane reactor systems are in progress that potentially could reduce POX process cost to the point where it would be very competitive with SMR even for low molecular weight hydrocarbons

Source: Open Access proceedings Journal of Physics: Conference series (iop.org)

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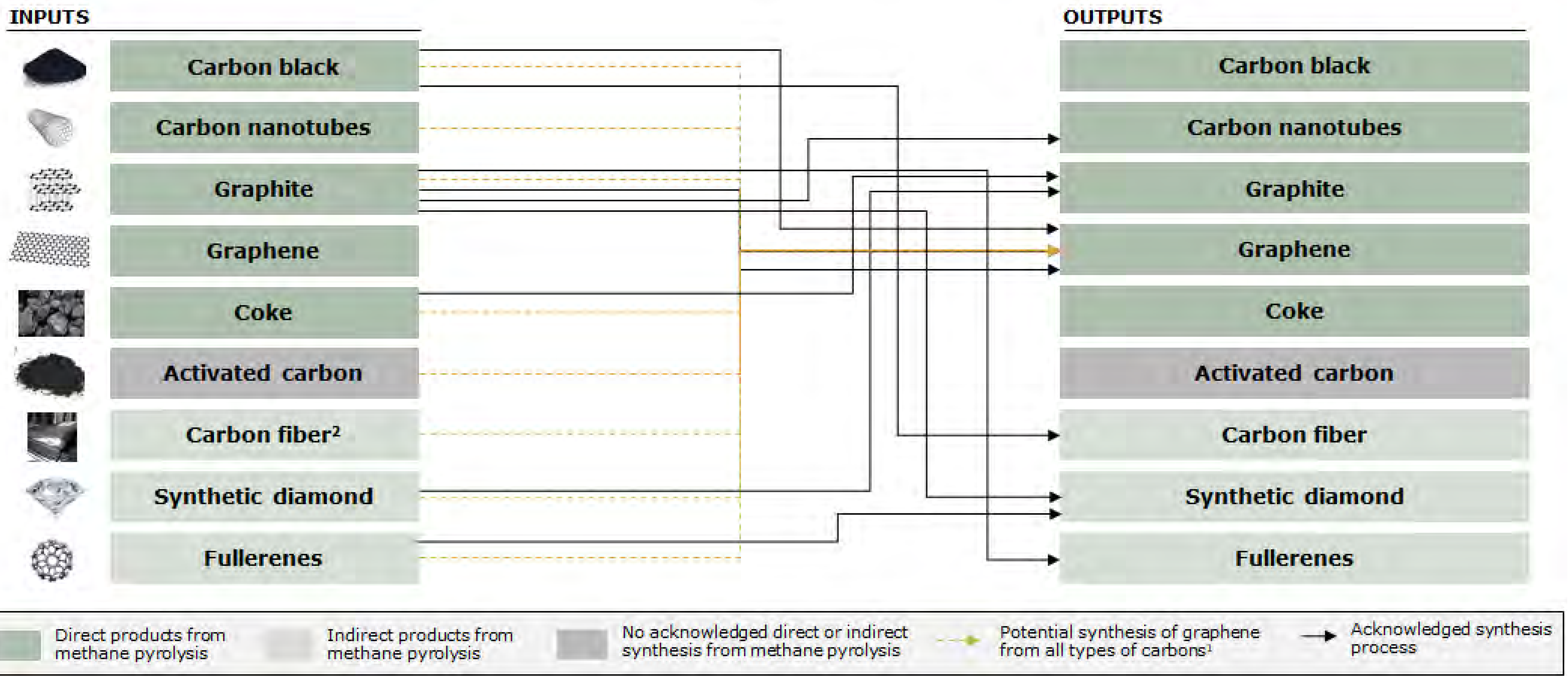
Methane pyrolysis offers an exciting route to new industries and bypasses the need for CCS which might benefit the smaller GCC states



Source: AFRY analysis 1. According to a RICE University (Houston, Texas) project dating from January 2020 by Pr J. Tour, 2: carbon fiber production from methane pyrolysis is theoretical, other production technology would be required

Carbon black and graphite could be produced by 4 technologies (out of 6), but at different levels of maturity

Type of solid carbon	**Production technology**					
	Thermal (non catalytic)	**Plasma**	**Microwave-plasma**	**Catalytic**	**Liquid metal / molten salts**	**Salt intermediaries**
Description	*Methane is injected in a high temperature reactor, resulting in thermal cracking*	*Methane is injected in an argon atmosphere with a plasma arc - requires electricity*	*Microwaves enable the decrease of process temperature - requires electricity*	*A catalyst (e.g. iron, copper, nickel, etc.) is used to generate hydrogen and carbon*	*Methane is conti-nuously decomposed in a reactor filled with liquid metal*	*Methane is reduced into carbon by using $NiCl_2$ as an inter-mediary reactor*
Coke	No	No	No	**Low**	**Low**	No
Carbon black	**Medium** *Large scale units are already existing to produce carbon, with low quality H2*	**Medium**	**Low**	No	**Low**	No
Graphite	No	No	**Low**	**Medium**	**Low**	**Low**
Graphene	No	No	**Low**	**Low**	No	No
Carbon nanotubes	No	No	No	**Medium**	**Low**	No

Low Maturity level // **High**: existing plants at industrial scale, **Medium**: on going pilot or development on going, **low**: others

Source: AFRY analysis

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Quality of carbon black and graphite from methane pyrolysis is sufficiently good for adoption in end-use applications

OPPORTUNITY FOR GCC

Graphite	– Graphite from methane pyrolysis has right quality and purity to be used as electrode for both LiB batteries and arc furnaces (e.g. in steel process)
Carbon Black	– Quality of carbon black seems to be adequate for applications like sealings, rubber filling and reinforcing, and hoses (fuel, coolant, etc.)
Graphene	– Quality of production of graphene from methane pyrolysis may not be sufficient (not homogenous, different flake sizes) – Applications for graphene are still scarce
CNT	– Output of carbon nanotubes from methane pyrolysis is not homogeneous – No large scale applications of CNT
Coke	– Coke cannot be used within the steel process (neither as a reductant nor for carbon content) due to particle size of output and limited strength of agglomerations
Carbon Fibre	– Carbon fibre cannot be a direct product from methane pyrolysis with current production technologies – Carbon fibre applications remain restricted to low volumes
Synthetic Diamond	– Synthetic diamond can be an indirect product from methane pyrolysis (via graphite HPHT process) – Small end-market with limited growth

Carbon black is the largest addressable market in term of volume – Graphite shows higher growth, thanks to increase in batteries for EVs and storage

	Applications	Demand (2018 – KT)	CAGR 2018 - 2040	Demand (2040 – KT)	
Carbon Black	**Total**	14.000 (100%)	4%	30.000 (100%)	
	Tires & tire components	7.957 (57%)	4%	17.000 (57%)	Rising automotive production
	Non-tire rubber products	4.230 (30%)	4%	9.000 (30%)	Rising product usage in the production of plastics
	Special blacks	1.813 (13%)	4%	4.000 (13%)	
Graphite	**Total**	2.500 (100%)	8%	15.000 (100%)	
	Refractories	828 (33%)	6%	3.000 (20%)	Graphite demand in automotive, construction, aerospace, and metal prod.
	Batteries	754 (30%)	11%	8.500 (57%)	Battery technologies and demand for energy storage (e.g. EVs)
	Others	918 (37%)	6%	3.500 (23%)	

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Graphite is currently used as an anode material to construct electrodes in major battery technologies

General description

- Global demand for batteries is growing strongly. A major component of these Lithium-Ion (LiB) batteries is the graphite used as the anode. The demand for the latter is constantly increasing.
- Graphite in the application of Lithium-ion batteries has the advantage of allowing the intercalation of Lithium atoms between its graphene layers to form an intercalation compound. It resists the exfoliation phenomenon and obtains low irreversibility during the first charge/discharge cycle.
- Two types of graphite are available for anode material:
  - natural graphite: it has a lower cost and a higher capacity, it is less Capex intensive, and it represents huge resources to be mined
  - synthetic graphite: it has a higher cycle life and produce higher power, it reduces expansion, and it has a higher stability
- Current ratio are approximately 40% natural graphite and 60% synthetic graphite used as anode for LIB. Often, synthetic and natural graphite are mixed together to get benefits from both

Value added of using graphite as anode material

- Excellent cycle life
- Low cost material
- High safety and good availability
- Good electrochemical properties
  - high efficiency and cycle stability
  - good reversible capacity (theoretical 372 mAh/g)
  - low potential vs. Li/Li+
- Good compatibility with other LiB components
- Relatively pure material compared to natural graphite

Source: IEA, 2021

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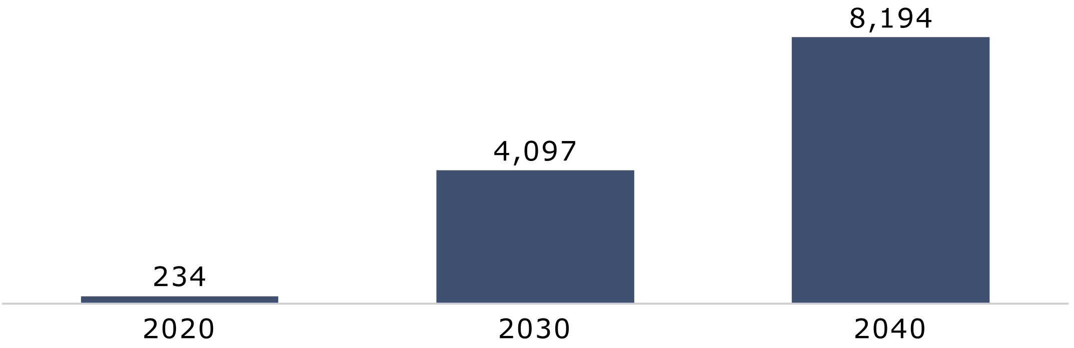
Market potential for graphite usage in battery in 2040 is estimated at USD 4 billion

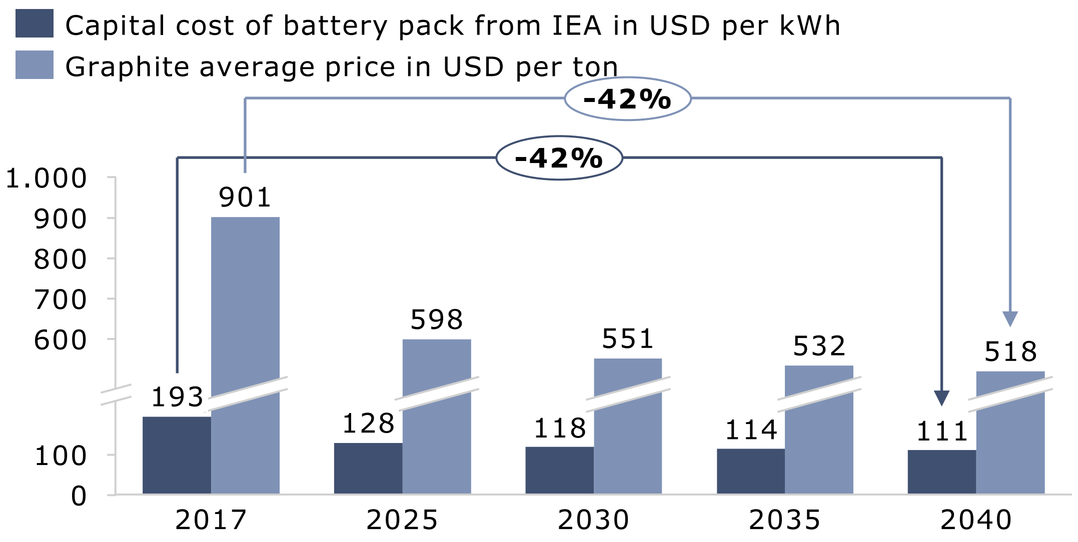
MARKET POTENTIAL FOR GRAPHITE IN KILOTONS

- IEA forecasts Lithium consumption for Electric Vehicles batteries to reach between 190 and 365 kilotons per year in 2030. There should be twice as much EVs produced in 2040 than in 2030.
- By weight, graphite is the second largest component in LiBs: they contain 10-15 times more graphite than lithium
- Taking an average value we obtain 3,688 in 2030 and 7,375 kilotons in 2040 of graphite produced for EVs batteries
- Electric mobility accounts for 90% of batteries production until 2030. We estimate the total batteries production based on EVs batteries previous value production

Evolution of graphite demand (in KT)



MARKET POTENTIAL IN USD



Note: we assumed that reduction of graphite price will follow reduction of battery price

Market potential in USD in 2040: USD 4 billion

Source: AFRY analysis

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Methane pyrolysis can support companies in their objectives to reduce their carbon footprint and to source lower cost raw materials

VALUE OF METHANE PYROLYSIS

Carbon Black supplier

TIRE MANUFACTURERS
– Carbon black from methane pyrolysis can be a lower carbon source for the production for tires and rubber, contributing to the current trend amongst companies to reduce their carbon footprint

ASPHALT/ CONCRETE
– Low cost carbon black from methane pyrolysis can provide asphalt & concrete producers with a filler material, while potentially providing add. properties (thermal resistivity, strength, colouring, amongst others)

MINING ABANDONMENT
– Methane pyrolysis produces high volumes of solid carbons at low costs that can be used to fill closed coal mines and replace ash from coal-fired power plants and paper mills, becoming more scarce

Graphite supplier

BATTERY MANUFACTURERS
– Methane pyrolysis can provide the synthetic graphite for the production of anodes for batteries, enabling a relocation of batteries towards Europe

REFRACTORY
– Methane pyrolysis could provide a cheaper and low carbon source of graphite supporting production growth

ELECTRODES
– Methane pyrolysis could provide a cheaper and low carbon source of graphite supporting production growth

H2

STEEL
– Methane pyrolysis could provide the low carbon hydrogen to green steel production

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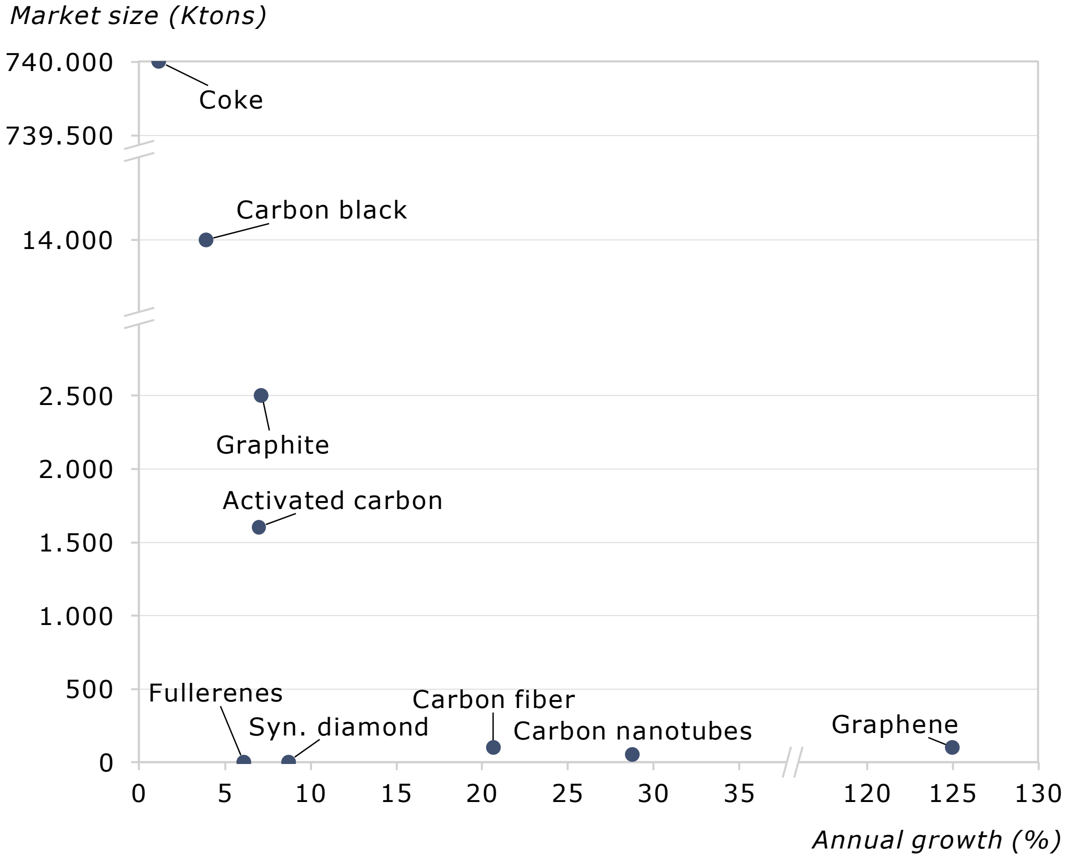
Coke is the largest carbon market (740 Mt/y), followed by carbon black (14 Mt/y) and graphite (2.5 Mt/y)

SOLID CARBONS MAPPING (MARKET SIZE IN KTONS)



CURRENT PRICE AND CAGR OF MAIN SOLID CARBONS

Total (kt/y)	758.450	Current price ($/t)	CAGR next 5 years (on volume)
Coke	740.000	115 – 230	~2%
Carbon black	14.000	580 – 1160	~4%
Graphite	2.500	1160– 6960	~6% (w/out batteries increase)
Activated carbon	1.600	1160 – 8120	~7%
Others[1]	350	N/A	N/A

Source: AFRY analysis, 1: others: Graphene, carbon nanotubes, carbon fibre, synthetic diamond, fullerenes

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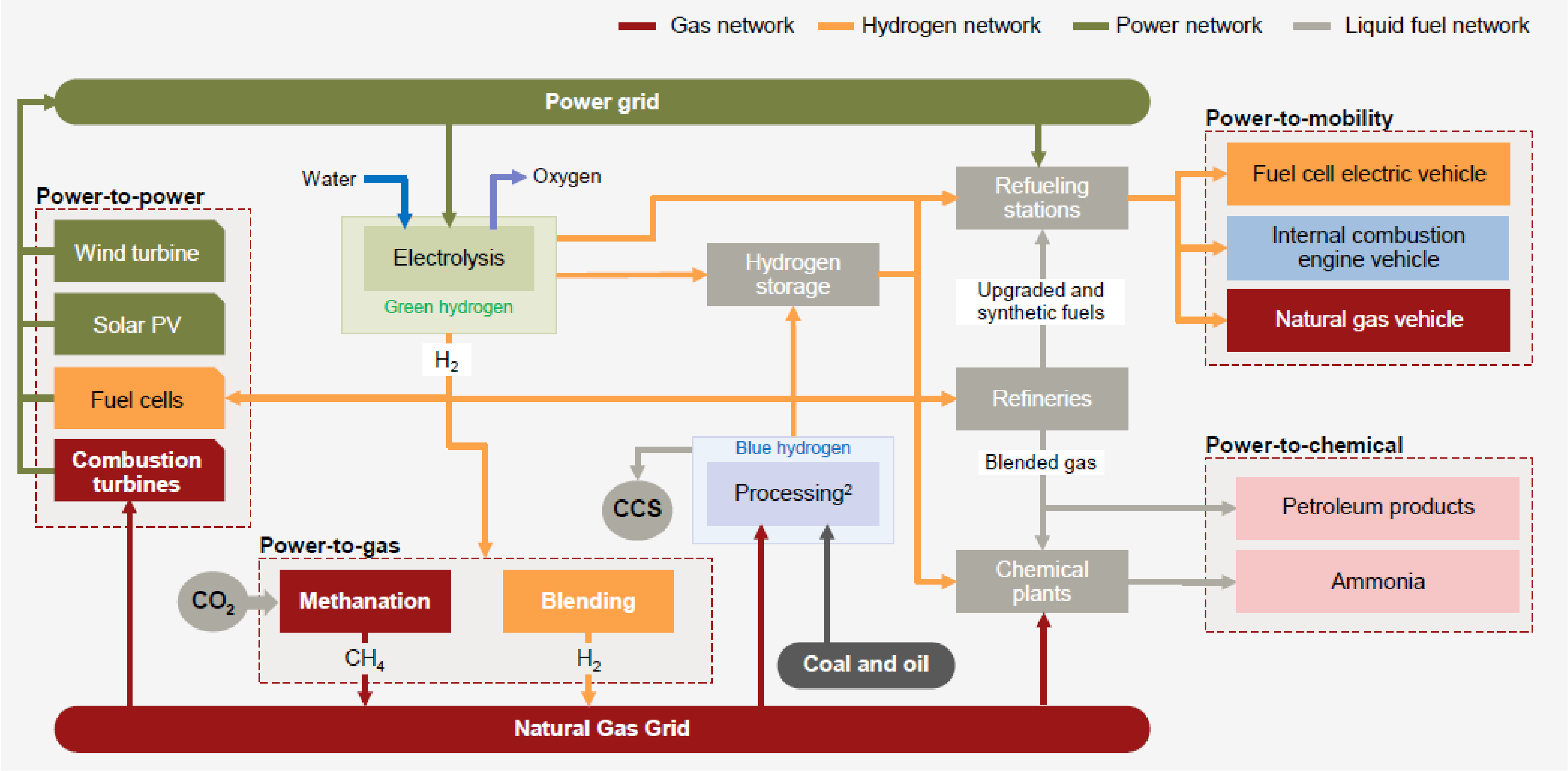
An integrated hydrogen system requires a transport and storage network both for domestic use and for exports



Hydrogen can be transported in solid, liquid and gas form with associated advantages and disadvantages

Material Based		Technology Description	Density (kg/m^3)	Energy Input		Process Maturity	Advantages	Disadvantages
				kWhr/kg H_2	(%LHV)			
Gas (pressure in bar)	35	Compression of H_2 at desired pressure to increase energy density	3	-1	-	High	PEM produces H_2 at 35bar pressure	Flammable
	150		11	~1	>90	High	Compression at 25°C	
	350		23	~4	>85	High		
	700		38	~6	80	High		
Liquified Hydrogen		Cooling of H_2 to -253°C by cryo-compression	71	~9	65-75	High for small scale Low for large scale	Economically viable where space is limited and high H_2 demand	High energy losses compared to LNG conversion Boil off losses (up to 1% per day)
Ammonia		Reaction with nitrogen	121	3 8 (recon)	82-93 ~80 (recon)	High for conversion, medium for reconversion	Mature industry, potential to leverage existing infrastructure	Toxicity and air polluter High energy required for reconversion
LOHC to MCH		Mixing with MCH and converted back to hydrogen	110	Exothermic ~12 (recon)	Exothermic ~65 (recon)	Medium	No need for cooling	Toxicity and flammability of toluene Price of toluene Back shipping of toluene
Metal hydrides		Chemical bonding with metal, reheat back to hydrogen	86 (MgH_2)	4	88	Medium	Lower costs and losses Higher safety Higher energy density than compression	Heavy storage unit Long charging/discharging times Low lifetime

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Hydrogen must be converted to another shipping/transport carrier to compensate for its low volumetric energy density in gaseous form

LIQUID HYDROGEN

Energy intensive conversion due to the low boiling point of hydrogen (-235 °C)
Significantly increases energy density of gaseous hydrogen (H2 at 1 bar: 0.01 MJ/litre -> H2 Liquid: 10 MJ/litre)

AMMONIA

- Easier to transport than hydrogen
- Could be used directly as ammonia by the importer if intended for that application, otherwise must be reconverted to hydrogen
- Less energy intensive than hydrogen liquefaction
- Ammonia already has a well-established international transmission and distribution network
- Toxic chemical

LOHC'S

- Easier to transport than hydrogen
- Cannot be used as final products and has to be reconverted to hydrogen
- Can be transported as liquids using oil tankers (similar properties to crude oil and oil products)
- Ship has to return loaded with the carriers

- For all three shipping methods, the fixed costs related to conversion and reconversion are the most significant portions of the total shipping cost, making up between 60-80% of total transport costs for a 10,000km journey. The marginal cost increase per km shipped is relatively minor, so longer distances make the case for shipping stronger
- Conditioning can be physical or chemical with the technique chosen to facilitate transport or storage, conditioning adds costs

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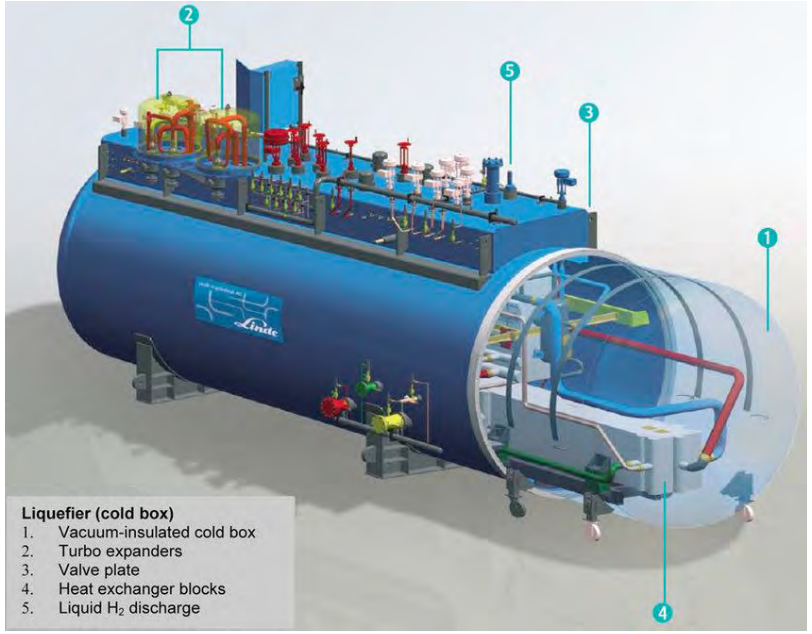
Liquefaction leads to losses from boil off but is a proven technology

DESCRIPTION

- Three step process:
- Hydrogen is first cooled with a liquid nitrogen heat exchanger
- Hydrogen is compressed and expanded in adiabatic conditions, cooling the gas and the system
- Isenthalpic Joule-Thomson expansion allows recovery of liquid H2
- Exothermic reaction owing to the nature of H_2 and in addition to these thermal losses due to non-perfect insulation, boil off occurs because of the heat emissions
- Shipping is inefficient as vessels would need to return empty unless a high value liquid could fill the tanks for the return journey

PROS	CONS
Easy reconversion High energy density Already used in the aerospace industry	Flammable Not mature for large-scale systems Boiling off, with losses of 0.3-1% per day

KEY FEATURES



Current cost estimate	\$1 per kgH_2
Typical size	5000-25000 kgH_2/day
Energy required (kWh/kgH_2)	10-13
Energy Consumption (% of LHV of hydrogen)	20-25, potential to 18

Ammonia can be reconverted into hydrogen or used as a feedstock for fertilisers

DESCRIPTION

- Synthesised through the Haber-Bosch process
- Reaction temperature is set at about 500°C at 20MPa to accelerate the reaction
- The catalyst used is iron and potassium hydroxide
- At each pass of gases through the reactor, only 15% of the hydrogen and nitrogen are converted to ammonia
- As a result the gases are recycled to increase conversion rate to 98%
- With a boiling point of -33°C, shipping vessels must be insulated, but boil-off is lower than for liquid hydrogen

PROS	CONS
High hydrogen density Low energy requirements Mature industry with existing infrastructure	Flammable Acute toxicity and air pollutant Corrosive Inefficient and non-mature reconversion process

KEY FEATURES

Current cost estimate	Conversion: \$0.98-1.2 per kgH_2 Reconversion: \$0.80-1.0 per kgH_2
Typical size	200000 kgH_2/day
Energy required (kWh/kgH_2)	Conversion: 2-3 Reconversion: 8
Energy Consumption (% of LHV of hydrogen)	Conversion: 7-18 Reconversion: Less than 20

LOHC’s do not require cooling and are safer to handle than ammonia, but need replacing with a 0.1% loss each conversion/reconversion cycle

DESCRIPTION

- Hydrogen is loaded on organic liquid through hydrogenation and dehydrogenated at the use point
- The hydrogenation process releases heat which can be used for alternative applications or for dehydrogenation
- Good candidates are relatively non-toxic, inexpensive, high storage capacity, low temperature conversion and reconversion reactions, and can withstand many cycles
- Toluene is a potential carrier for hydrogen by converting it to MethylCycloHexane (MCH)
- DiBenzylToluene (DBT) is an alternative to MCH and is reported to be safer, easier to handle and cheaper
- Shipping consumes more fuel due to the heavier weight, but could re-use existing tankers

PROS	CONS
Liquid in ambient conditions, opportunity to re-use oil infrastructure Fluid carrier is reusable No boil-off losses	MCH is toxic Dehydrogenation is energy intensive to reach 250-350°C Need to ship back once the carrier is dehydrogenised

KEY FEATURES

Current cost estimate	Conversion: \$1 per kgH_2 Reconversion: \$2.1 per kgH_2
Typical size	10000 kgH_2/day
Energy required (kWh/kgH_2)	10
Energy Consumption (% of LHV of hydrogen)	35-40, potential to 25

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Metal hydrides improve hydrogen handling safety but are yet to be proven economically feasible

DESCRIPTION

- Certain metals bond strongly with hydrogen forming a metal hydride compound
- When the hydride is heated the metal-hydrogen bonds break and recombine into hydrogen molecules
- To minimise the energy penalty heat from the process can be coupled
- Combined thermal storage and metal hydrides is already on the market (adiabatic metal hydrides)
- Currently being considered for niche applications, such as military, where stability is the key

PROS	CONS
Low pressure operation with lower costs and losses Safer than compressed gas or liquid hydrogen Larger energy capacity	Attaching hydrogen to metal results in a heavy storage unit Long charging and discharging times Low lifetime

KEY FEATURES

Current cost estimate	N/A per kgH_2
Typical size	10-20MWh
Volumetric density (kWh/m3)	4200
Efficiency (%)	80-90

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Ammonia offers the most versatile solution for at scale storage and transport, other mediums more suited to local demands

Transformation method		Long Distance transportation		Short distance distribution			Storage			
Physical	Compression	X	X	X	X	X	X	X		X
Physical	Liquefaction		X		X	X	X			
Chemical	Ammonia	X	X	X	X	X	X	X		
Chemical	LOHC		X		X	X	X			
Chemical	Hydrides		X		X	X			X	
Scale		~2000km	>3000km	<500km	<500km	<1000km	Small-mid	Small-mid	Small	Large

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Pressurised tanks are the most mature and common hydrogen storage solution

DESCRIPTION

- To increase its energy density, hydrogen can be compressed and stored in pressurised tanks of various scales
- Tank storage compressed or liquified hydrogen have high discharge rates and efficiencies
- Pressurised tanks need a high operational cycling rate to be economically feasible
- If the storage time relative to the power rating increases beyond a few days the capital costs of vessels and compressors become a drawback for this technology
- Research continues with the aim of reducing the size of the tanks for densely populated areas

PROS	CONS
Mature Technology Fast charge and recharge time Easy to transport	Low volumetric and gravimetric density resulting in large and heavy tanks Low storage capacity per vessel

KEY FEATURES

Current cost estimate	\$6000-10000 per MWh (storage tank)
Typical size	100kWh-10MWh per tank
Volumetric density (kWh/m3)	670-1300
Efficiency (%)	89-91 (350bar) 85-88 (700bar)

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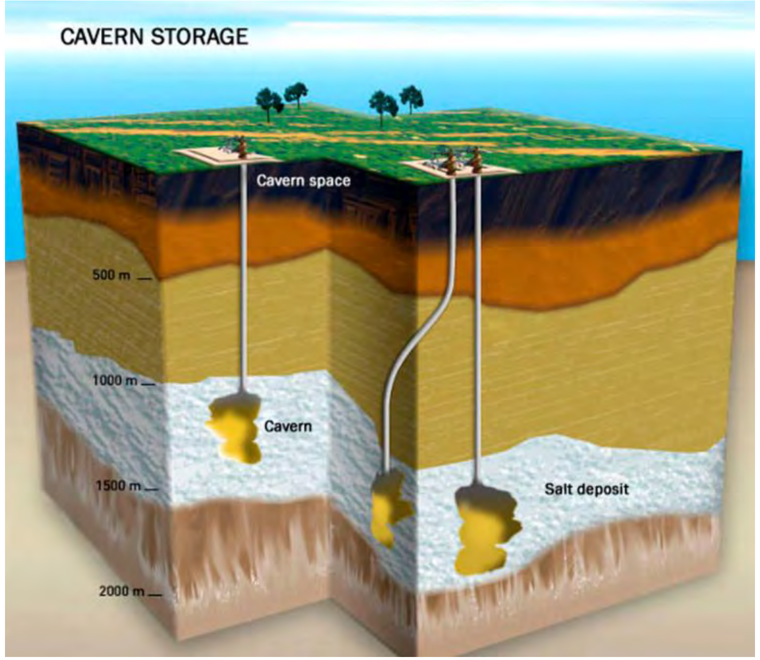
Geological storage, particularly salt caverns are potential storage options for large-scale and long-term hydrogen storage

DESCRIPTION

- Hydrogen gas is injected and compressed in underground salt caverns, which are excavated and shaped by injecting water into existing rock salt formations
- Withdrawal and compressor units extract the gas when required
- Mature technology – have been used since the 1970's in the UK and the 1980's in the USA
- Other underground options exist such as depleted oil and gas reservoirs and aquifers – but they are more permeable and contain contaminants
- Aquifers were used to store town gas with 50-60% hydrogen without issue, but are less mature for geological storage overall

PROS	CONS
High volume storage at lower pressure and cost Seasonal storage Low risk of contaminating the stored hydrogen	Geographical specificity, large size and minimum pressure requirements Less suitable for short-term and smaller scale storage

KEY FEATURES



Current cost estimate	Less than $0.6 per kgH$_2$
Typical size	1-1000GWh
Volumetric density (kWh/m3)	65 (AT 100bar)
Efficiency (%)	90-95

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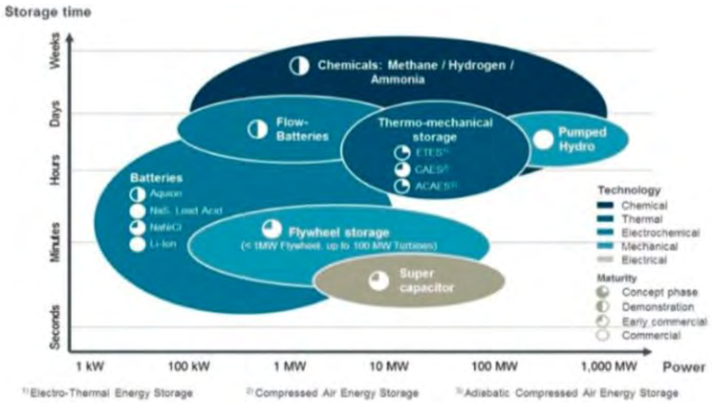
Compressed hydrogen storage in salt caverns offers the most economic option for long term storage

DESCRIPTION

- Hydrogen compressed as a gas in salt caverns is a viable route for seasonal storage and to balance renewable energy generation or to smooth electricity demand
- Compressed hydrogen suffers from low round trip efficiency (60% of the original electricity is lost)
- Other potential solutions include pumped hydro storage, batteries and thermo mechanical storage technologies
- The storing of hydrogen-based fuels such as methane, (LOHC's) liquid organic hydrogen carriers (such as methanol, Toluene/methylcyclohexane, N-ethyl carbazole, Dibenzyltoluene) and ammonia in respective vessels is also a viable storage route and likely to prove more cost effective for long-range exports

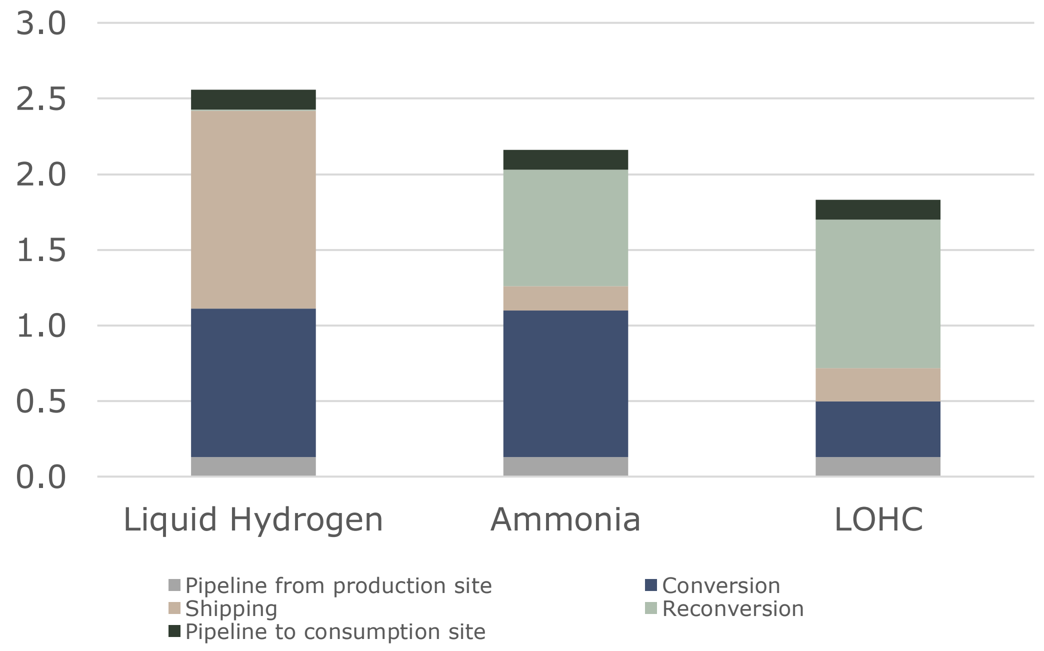
KEY FEATURES



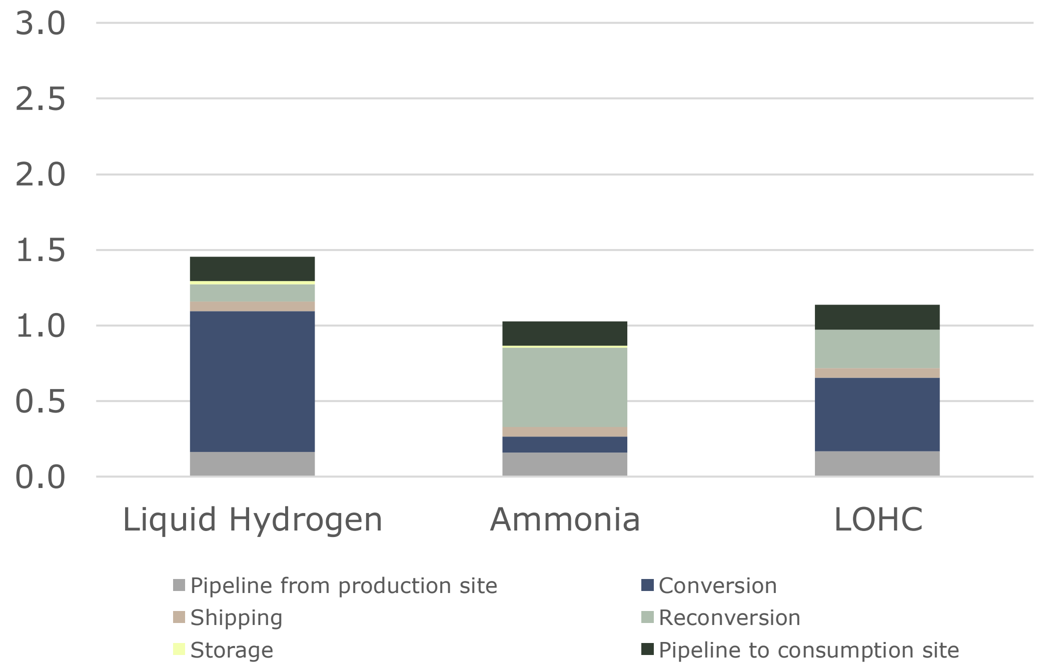
Parameter	Units	PHES	CAES	Li-ion	Compressed H_2
CAPEX (power)	$/kWh	1130	870	95	1820
CAPEX (storage)	$/kWh	80	39	110	0.25
OPEX (power)	$/kWh	8	4	10	73
OPEX (storage)	$/kWh	1	4	3	0
Round-trip efficiency	%	78	44	86	37
Lifetime	Years	55	30	13	20

There are variations in the levelized cost of hydrogen transport calculations between different sources, but all add $1-3 on production costs

IEA – FUTURE OF HYDROGEN ($/KG,$H_2$)



EUROPEAN HYDROGEN BACKBONE ($/KG,$H_2$)



- The levelized cost of hydrogen transport assumes that it is transported via pipeline, in gaseous form, between production sites and export terminals, and between import terminals and consumptions sites. Hydrogen is converted and reconverted to and from other carrier forms at the export and import terminals respectively
- Storage costs are embedded in the various cost components in the IEA calculations
- Significant discrepancies arise on shipping and conversion components of the transport process

Sources: IEA, European Hydrogen Backbone

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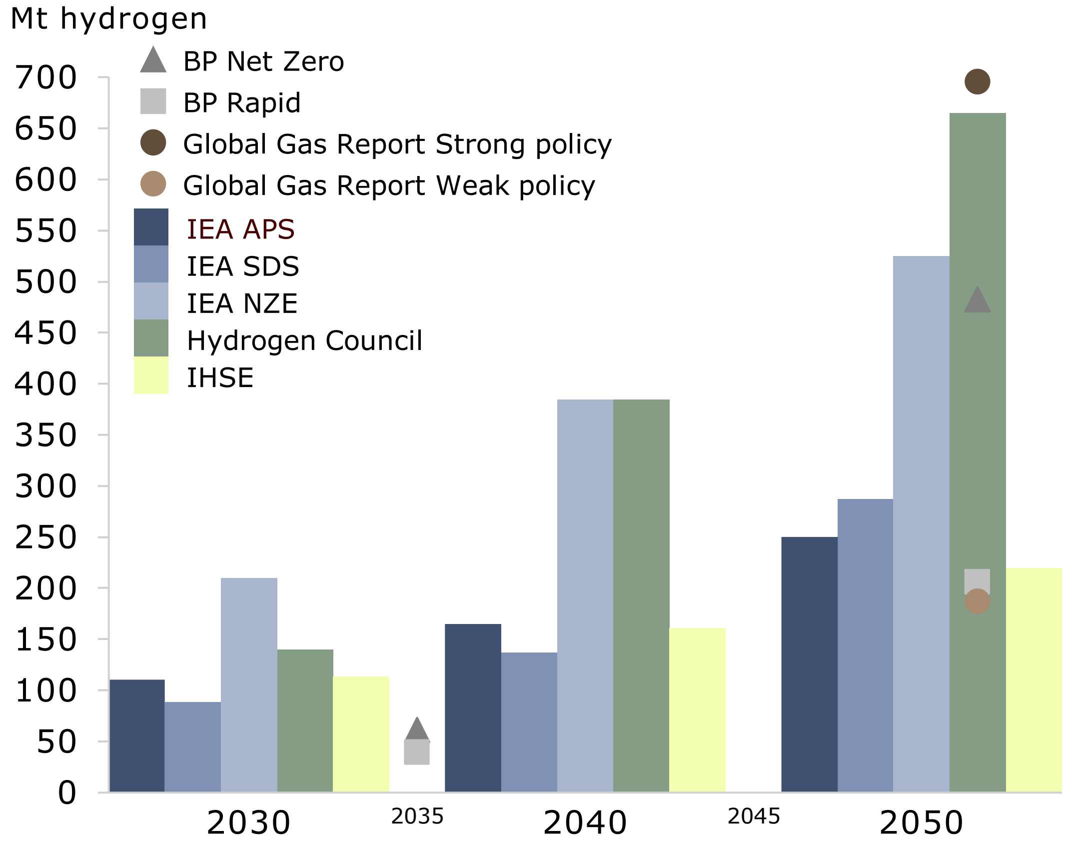
The Hydrogen Council estimates global hydrogen demand at 660 million tonnes per annum by 2050, much of which could be supplied by the GCC

HYDROGEN GLOBAL DEMAND OUTLOOK



COMMENTARY

- Global demand for pure hydrogen in 2019 was over 70 Mt, mostly coming from oil refining and ammonia production for fertilisers.
- The Hydrogen Council's recent forecast suggests that global hydrogen demand is expected to reach 660 million tonnes in 2050 driven by growth in hydrogen mobility and the use of hydrogen in industrial activities and heating
- Most scenarios project demand above 100 Mt by 2030, according to the rapid-decarbonisation IEA Net Zero (NZE) scenario, global demand will reach over 200 Mt in 2030.
- Despite the slow growth between 2020 and 2030, hydrogen demand is expected to almost triple between 2030 and 2040 as more hydrogen is utilised in buildings and industrial heat generation, and the transport sector switches to hydrogen mobility
- By 2050, lowest demand of 220 Mt is expected which is a third of the hydrogen councils projection, the role of hydrogen in power generation remains limited compared to global renewable energy generation

Notes: BP scenarios from BP 2020 Energy Outlook | Global Gas report scenarios from Snam, IGU and BNEF, Global Gas Report 2020 | IEA APS = Announced Pledges Scenario; NZE = Net Zero Scenario from Global Hydrogen Review 2021 and SDS = Sustainable Development Scenario from Energy Technology Perspectives 2020 | Hydrogen Council scenario from the Hydrogen Council and McKinsey 2021 publication Hydrogen For Net Zero

The most promising sectors for hydrogen are industry, transport and power…

Industry

- The top four existing uses of hydrogen in the industrial sector are:
  - Oil refining (33%)
  - Ammonia production (27%)
  - Methanol production (11%)
  - Steel production via the direct reduction of iron ore (3%)

- **Oil refining**
  The largest end-use of hydrogen where hydrogen is primarily used to remove impurities, especially sulphur from crude oil and to upgrade heavier crude.
- **Ammonia and methanol**
  Primary chemicals require large quantities of dedicated hydrogen production for use as feedstock, notably ammonia and methanol.
- **Iron and steel**
  The fourth largest source of hydrogen demand where a mixture of hydrogen and carbon monoxide is used as a reducing agent.

Transport

- Hydrogen fuel cell electric vehicles (FCEVs), such as light and heavy-duty vehicles, trains, ships, planes, and drones, are expected to play an increased role in the near future.

- **Passenger car**
  FCEVs are unlikely to be competitive with BEVs in the smaller passenger sector due to the higher Total Cost of Ownership (TCO).
- **Light and heavy-duty vehicles**
  FCEVs are most likely to be used in heavy transport because the fast-refueling time and driving range are comparable to gasoline-powered trucks and travel routes are predictable.

Power

- In the near term, ammonia could be co-fired in coal-fired power plants to reduce CO_2 emissions (Japan and Korea have plans to do this).
- Hydrogen and ammonia can be a flexible generation option when used in gas turbines or fuel cells.

- **Hydrogen gas turbines**
  This option, including CCGTs, is technically feasible and can be designed to operate with 100% hydrogen to produce power flexibly to support increased renewables energy.
- **Hydrogen fuel cells**
  A combination of hydrogen and oxygen to produce water and generate electricity in the process.

Source: AFRY

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…and when considering factors that will determine its success, the horizon for competitiveness is frequently between 2030 and 2040

FACTORS FOR COMPETITIVNESS

Industry

- Future hydrogen demand in oil refining is dependent on future oil demand but may be boosted by tighter pollution regulations
- Future demand for hydrogen in the chemical sector is dependent on the increase in demand for ammonia and methanol and for plastic chemical recycling.
- Future hydrogen demand in iron and steel production is dependent on shifting steel production to the DRI route and the growth of global steel demand.

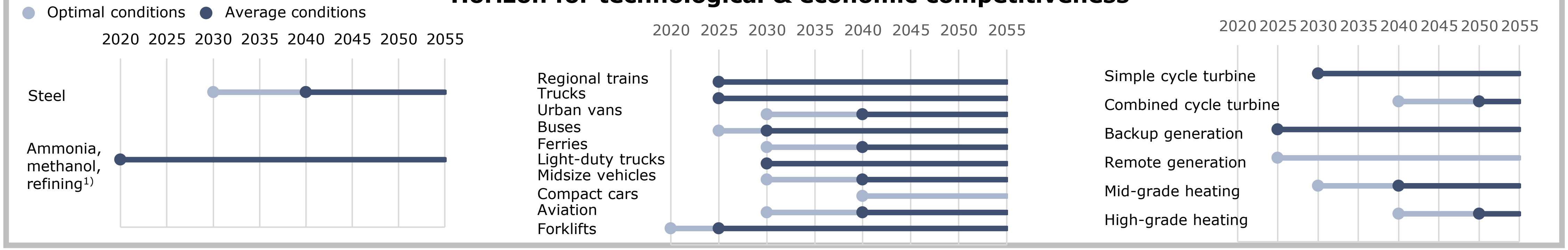
Transport

- The competitiveness of hydrogen FCEVs depends on fuel cell costs and the building and utilisation of refueling stations, which are limited to date.
  - For cars, the priority is to bring down the cost of fuel cells and onboard hydrogen storage to make them competitive with BEVs at driving ranges of 400–500 km.
  - For trucks, the challenge is to reduce the delivered price of hydrogen.

Power

- Hydrogen has the potential to be used in power systems for low-carbon and seasonal storage.
- Key low-carbon competitors for hydrogen services in power sector include natural gas with CCUS, biomethane and other forms of seasonal storage.
- A hydrogen cost under USD 2.5/kg has the potential to compete with alternative sources, depending on the country and power sector conditions.

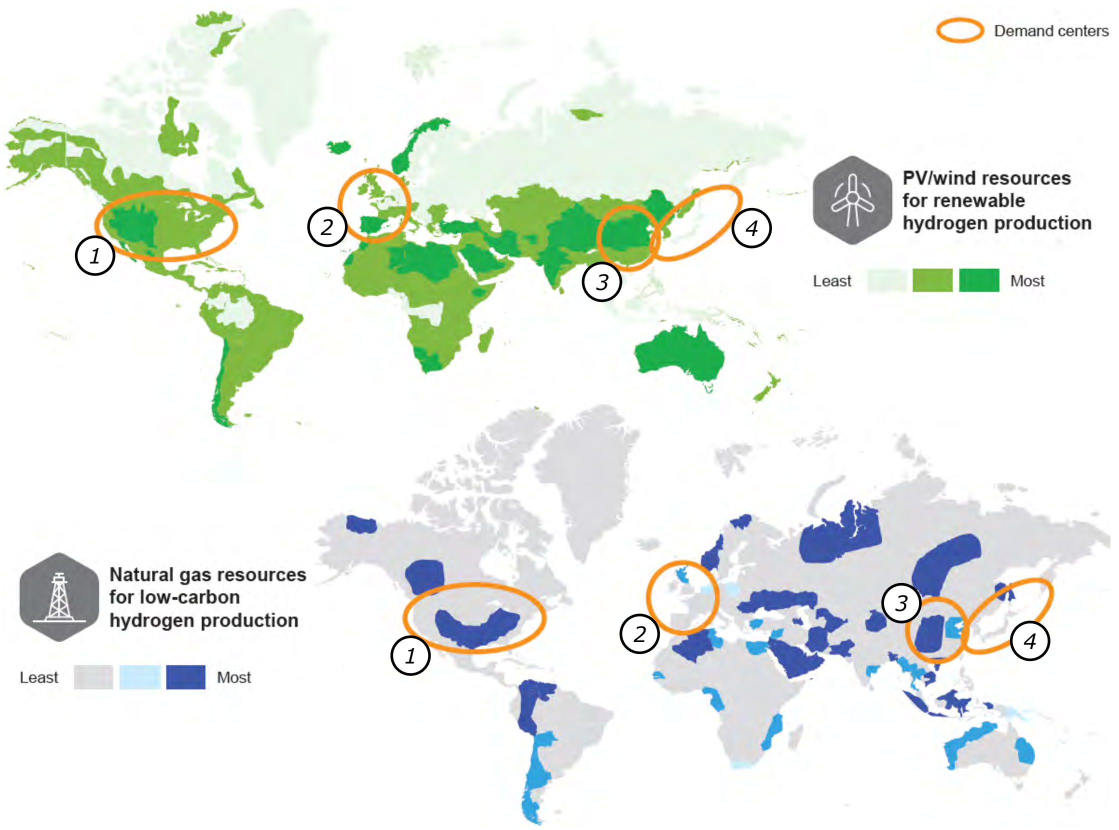
Horizon for technological & economic competitiveness



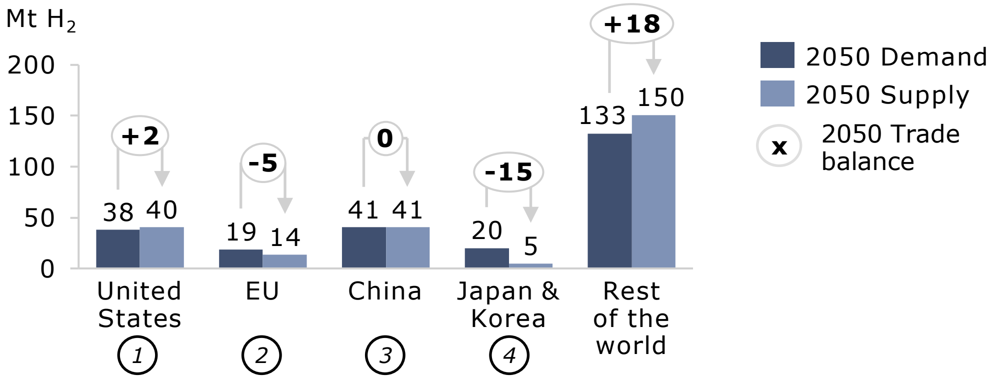
Source: AFRY; Bain and Company (2021), When will hydrogen be cost-competitive | Notes: 1) For ammonia, methanol and refining, grey hydrogen is used as a feedstock today.

Countries with good natural resources and demand centre's do not always coincide…

HYDROGEN DEMAND CENTERS AND NATURAL RESOURCES, 2050



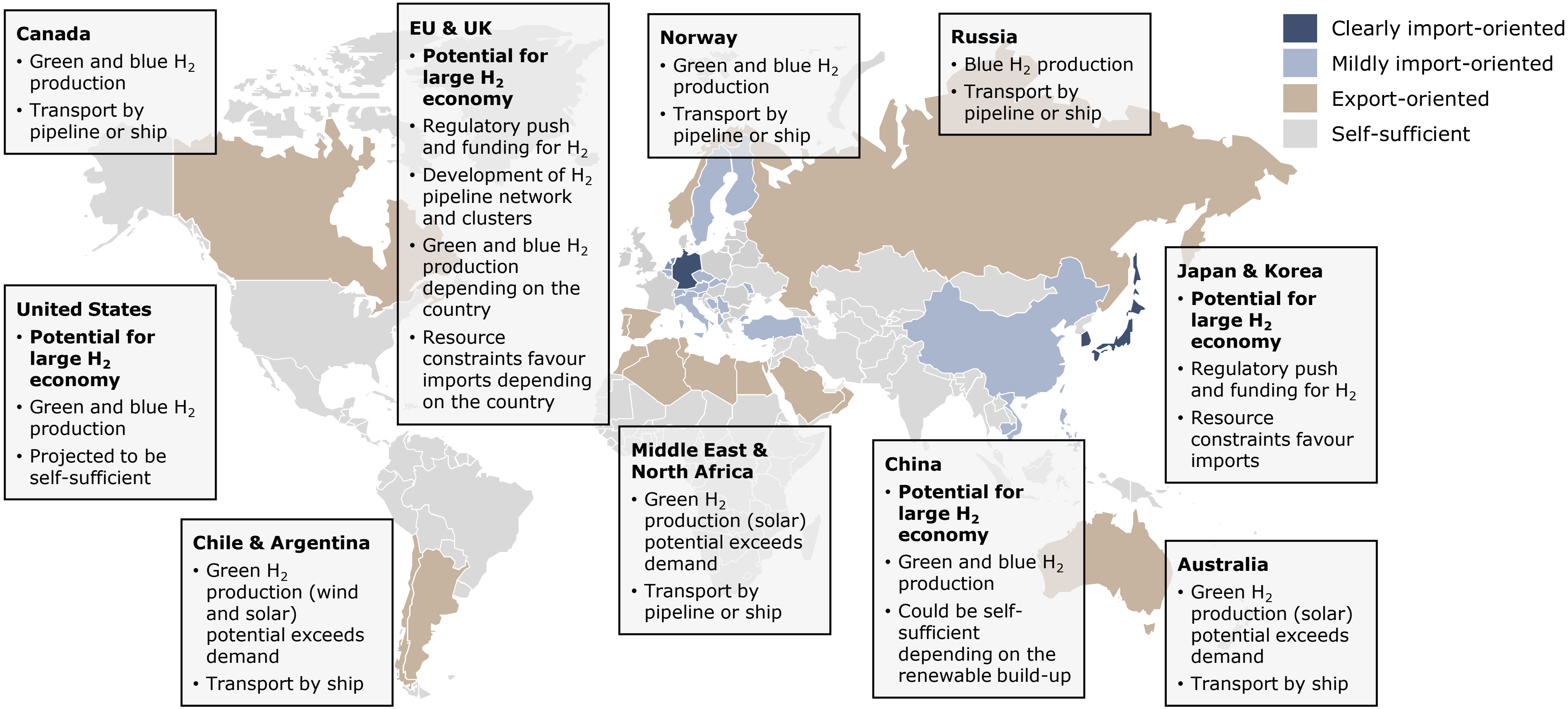
IEA APS[1)] ESTIMATED ANNUAL H_2 DEMAND/SUPPLY BY REGION IN 2050



- Various factors could lead to differences in obtaining blue and green hydrogen across regions. These factors include:
  - the availability of renewable resources
  - the availability of natural gas sites
  - existing infrastructure
  - land-use constraints
  - assignment of renewables capacity for direct electrification
  - the availability of competitive transportation technologies

Source: IEA; Hydrogen Council 2021; AFRY analysis | Note: 1) the demand reported is from the IEA Announced Pledges Scenario (APS)

… which could lead to the need to import and export low-carbon hydrogen

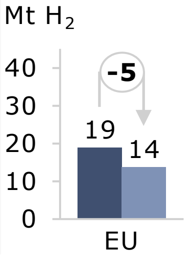


Source: AFRY; BNEF (2020), Hydrogen Economy Outlook; Strategy& (2020), The dawn of green hydrogen: Maintaining the GCC's edge in a decarbonized world

The EU, Japan and Korea are expected to be the most important demand centres in need of a total of 20Mt H_2 in 2050 of imports, according to IEA[1)]

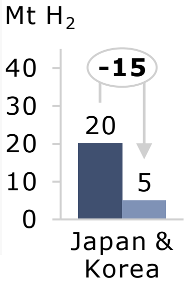
EU

- Potential for a large hydrogen economy
- Regulatory push and funding for hydrogen
- Development of a European hydrogen pipeline network and clusters
- Green and blue hydrogen production depending on the country
- **Resource constraints favour imports depending on the region**



Japan & Korea

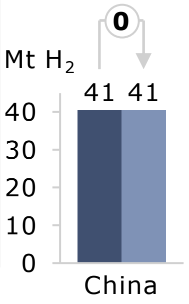
- Potential for large hydrogen economy
- Regulatory push and funding for hydrogen
- **Resource constraints favour imports**



2050 Demand
2050 Supply
x 2050 Trade balance

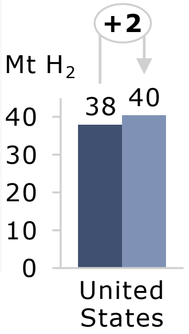
China

- Potential for large hydrogen economy
- Green and blue hydrogen production
- Could be self-sufficient depending on the renewable build-up



USA

- Potential for large hydrogen economy
- Green and blue hydrogen production
- Projected to be self-sufficient



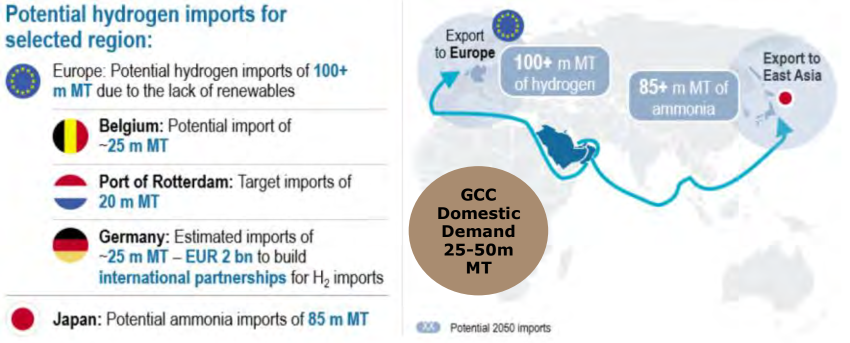
- The demand and supply values shown are from the IEA APS[1)], a conservative scenario regarding the demand and supply of hydrogen
- Other scenarios may project higher demand and/or supply for each region and may lead to a larger volume of import required

Source: AFRY analysis | Notes: 1) demand and supply projections from IEA Announced Pledges Scenario (APS), as the equivalent figure is not available from other IEA scenarios.

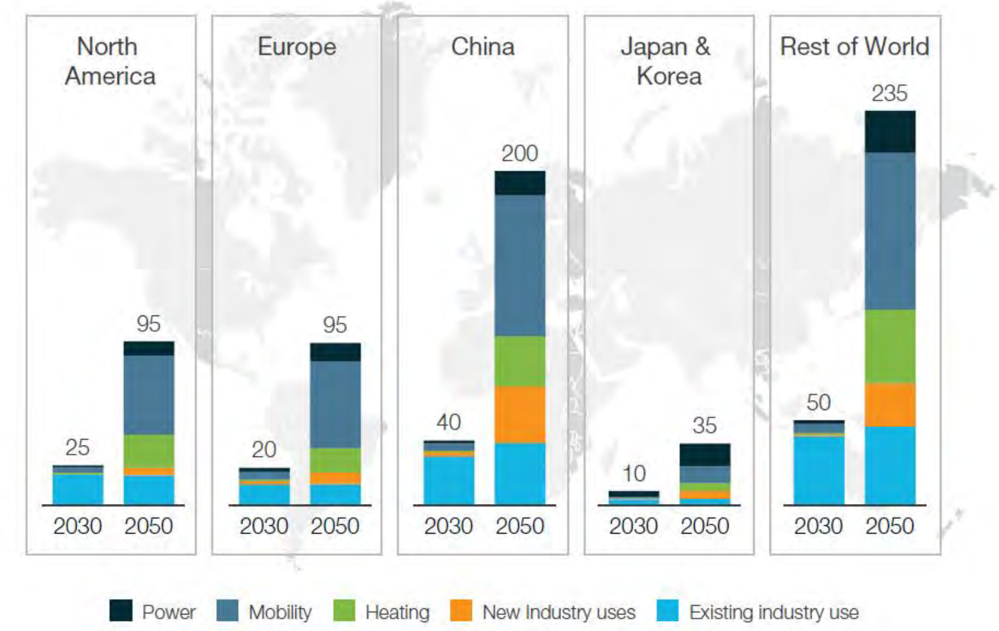
The proximity of the GCC region to Europe and East Asia makes them ideal for future hydrogen exports, but a regional market also exists

DESCRIPTION

- Asia will dominate hydrogen demand by mid century but shorter term Europe is a more attractive destination
- As of today, 39 countries have published their hydrogen strategies with Europe and East Asia leading the transition
- Hydrogen strategies of Japan, South Korea, and other countries in Europe highlight the importance of hydrogen imports in meeting their future targets
- European hydrogen imports are expected to grow to 100 Mtpa in 2050. Germany and Belgium are expected to import 25 Mtpa each while the Port of Rotterdam imports could amount to 20 Mtpa based on Vision Port of Rotterdam
- The Asian market will be driven by China, Japan, and South Korea. In 2050, Japan could require 85 Mtpa in ammonia imports



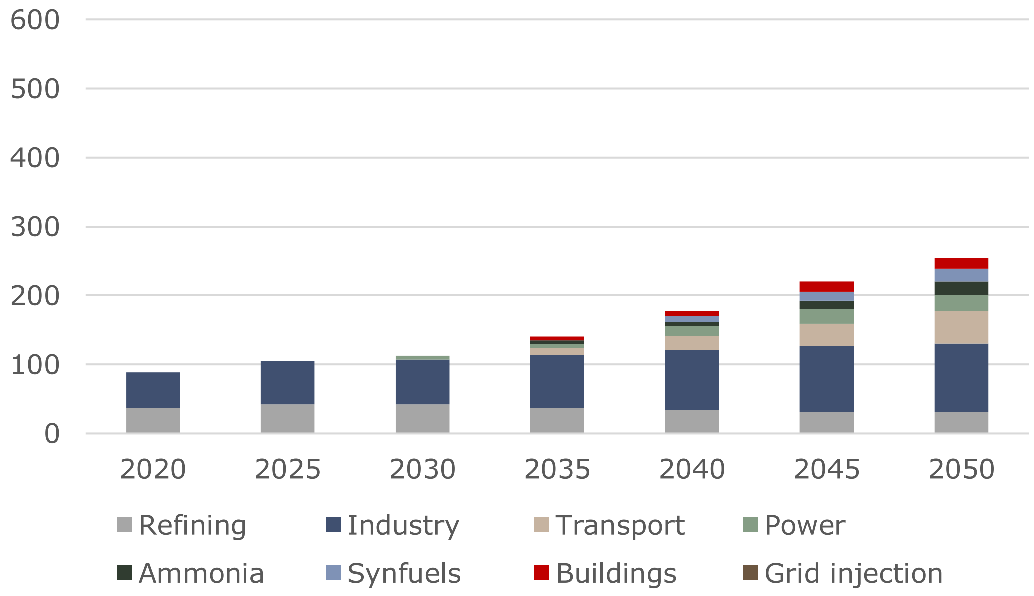
POTENTIAL HYDROGEN IMPORTS IN EUROPE AND ASIA



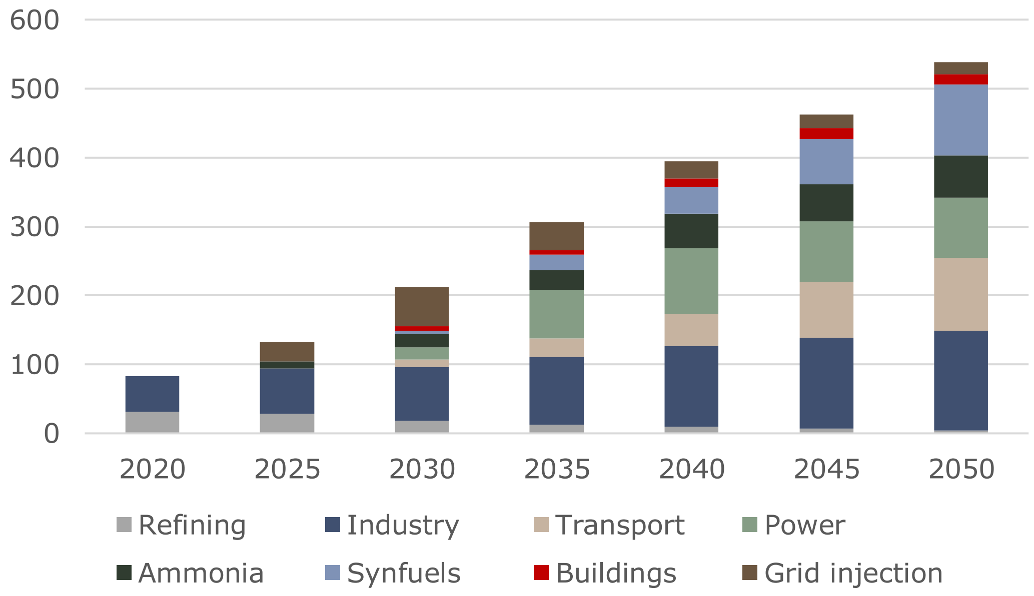
Sources: Vision Port of Rotterdam, Germany H2 Strategy, EU H2 Strategy

The extent of future hydrogen demand hinges on policy support to make it an attractive energy carrier

ANNOUNCED PLEDGES SCENARIO – MILLION TONNES H2



NET ZERO SCENARIO – MILLION TONNES H2



- According to the IEA, hydrogen demand will be short of 300 Mtpa in 2050 in the absence of policy support given that 530 Mtpa of hydrogen demand is required to achieve the net zero target
- In the Net Zero Scenario, hydrogen demand is driven by its central role in the transport, power and petrochemical sectors
- The IEA states that the Middle East, Chile, and Australia will emerge as key exporting regions in the Announced Pledges Scenario benefitting from the low-cost of producing hydrogen from renewables or from natural gas with CCUS
- The IEA estimates 2050 hydrogen exports from North Africa, the Middle East, and Chile to Europe to reach 600 PJ per annum, while Middle East exports to Japan and South Korea could amount to 1000 PJ per annum

The GCC has the resources and opportunity to be a leader in hydrogen, but will need to take risks if it wants to compete globally

STRENGTH

- World class solar resources and localized wind
- Qatar has lowest cost feedstock for blue hydrogen route
- Established infrastructure for export of hydrogen and derivatives
- Proven ability to export low carbon ammonia

WEAKNESS

- Limited hydrogen market within states, the GCC and globally
- No clear route for pipelines to supply key markets, export limited to ship-based solutions
- Hydrogen will not be able to wholly replace oil and gas revenues
- Significant expansion of renewables required both for green and to free gas for blue

THREAT

- Lack of carbon price and business model for CCS
- Uneven distribution of potential may push states into competition instead of collaboration
- Other countries are moving faster in developing capacity and an export market
- States lock in legacy positions in oil and gas and react too slow to the transition

OPPORTUNITY

- Huge decarbonization potential across the GCC in hubs
- Well placed to serve the global export market
- Export of products and derivatives rather than raw materials
- Pyrolysis offers whole new suite of industries

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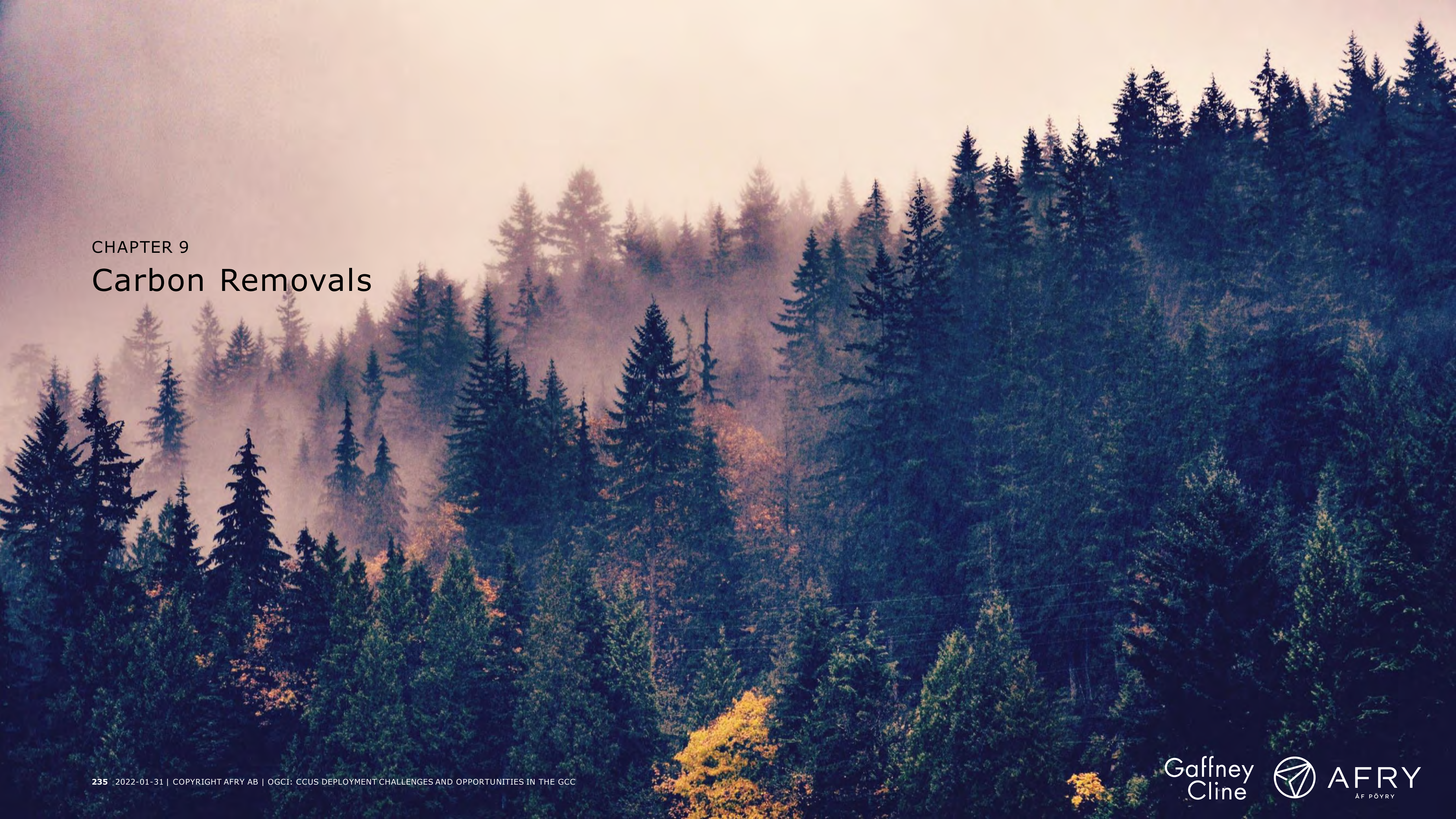

CHAPTER 9

Carbon Removals

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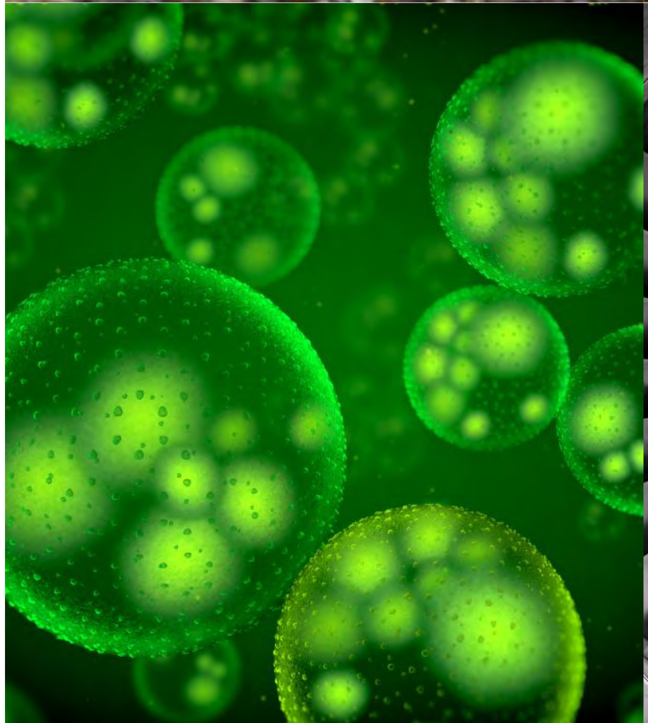
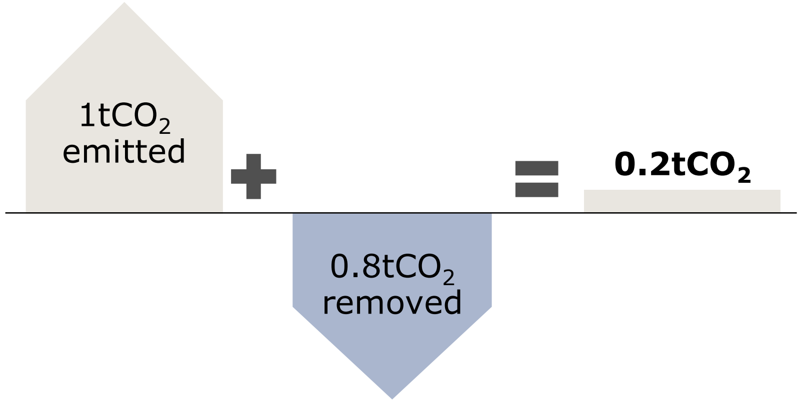


Carbon capture alone will not be sufficient for decarbonisation and technologies that remove carbon from the atmosphere are needed

CARBON CAPTURE AND STORAGE (CCS)

- CO_2 captured from fossil fuel combustion
- CO_2 stored
- Emissions reduced, but still net-positive

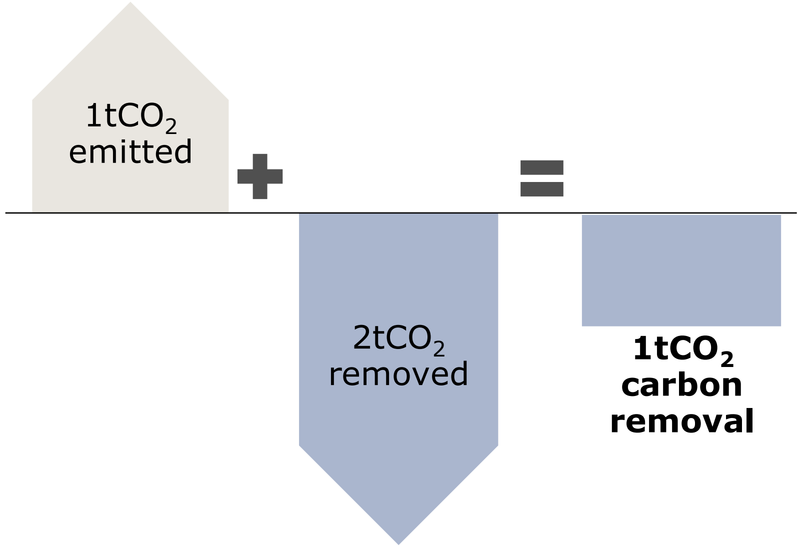
Not a carbon removal because i) capture is from fossil fuel and ii) process is not net-negative



REFORESTATION, BECCS, DACCS ETC

- CO_2 captured from **atmosphere** ✓
- CO_2 stored ✓
- **Net-negative** ✓

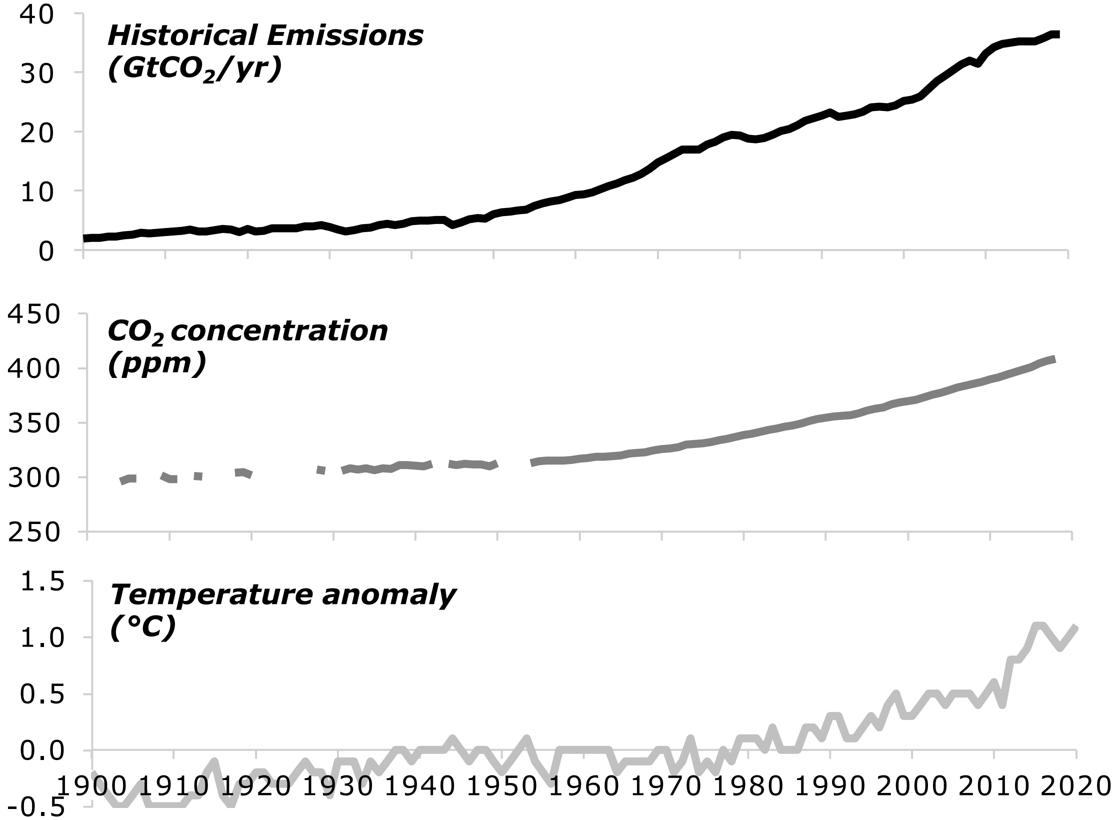
Carbon removal



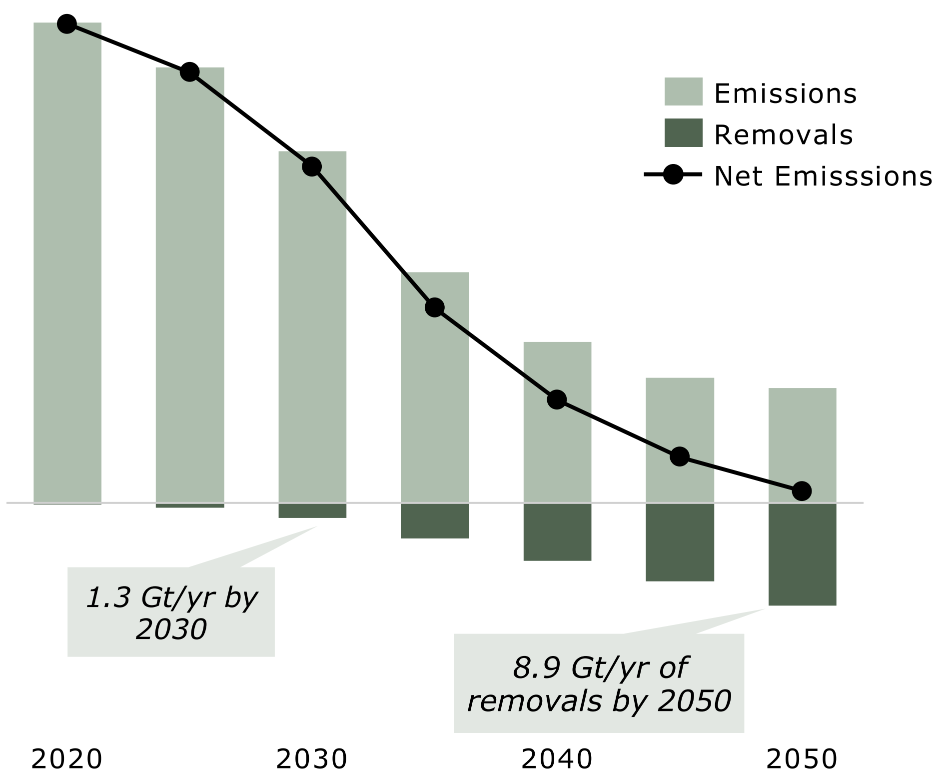
Values shown in these examples are purely illustrative and are focused on emissions and removals within the boundary of the project e.g. we do not include the avoided emissions that occur as a result of replacing fossil plant

Carbon removals are required to stabilise global temperatures and to reduce temperatures should we overshoot acceptable levels

TEMPERATURES RISE DUE TO CUMULATIVE EMISSIONS



IPCC 1.5ºC PATHWAY TO NET-ZERO *($GTCO_2$/YR*



Left: Annual production-based emissions – Global Carbon Project (2020); Atmospheric CO_2 concentration in parts per million (ppm) – NOAA (2018); Temperature anomaly relative to 1961-1990 average – Hadley Centre (HadCRUT4). Middle: Adapted from Swiss RE. Right: Adapted from IPCC (2018) Special report: global warming of 1.5ºC (Table 2.4 – 1.5ºC with high overshoot pathway) – removals here is represented by BECCS + AFOLU. IEA net zero scenario - DACCS: 71Mt/yr and 633Mt/yr for 2030 and 2050 respectively.

Demand for carbon removal is set to climb in order to fulfil net zero ambitions – from both the regulated and voluntary markets

NUMBER OF NET ZERO COMMITMENTS ARE INCREASING*

120
governments

EU aims to be climate-neutral continent by 2050

China to become carbon-neutral by 2060

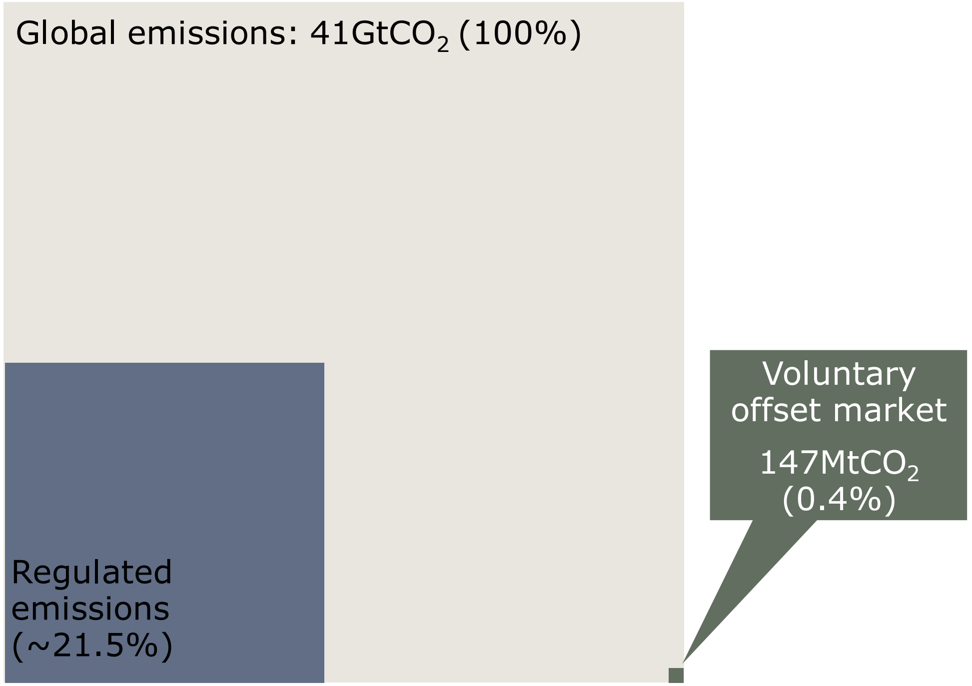
3,067
businesses

"Carbon negative by 2030. Remove historical carbon emissions by 2050"

733
cities

31 regions,
622 universities

CARBON MARKETS ARE SET TO EXPAND



* UN's "Race to Zero" initiative – collectively these actors now cover nearly 25% global CO_2 emissions and over 50% of global GDP.

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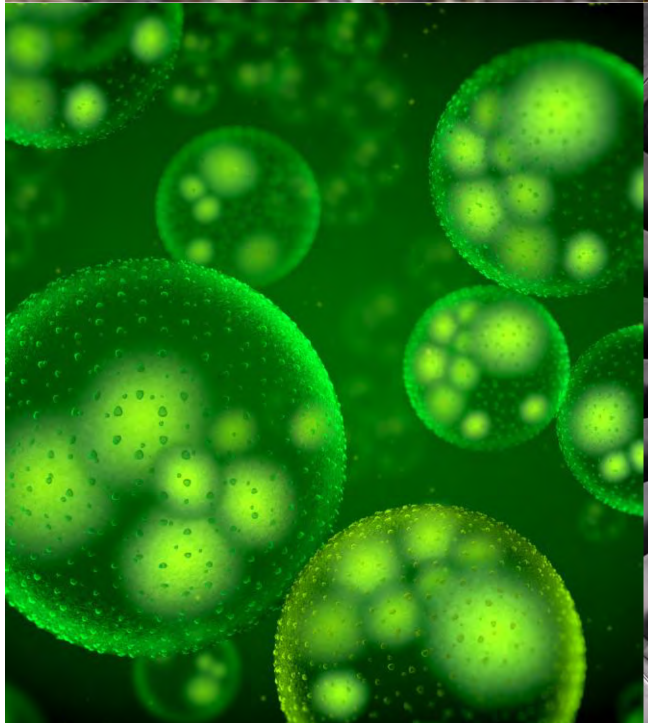
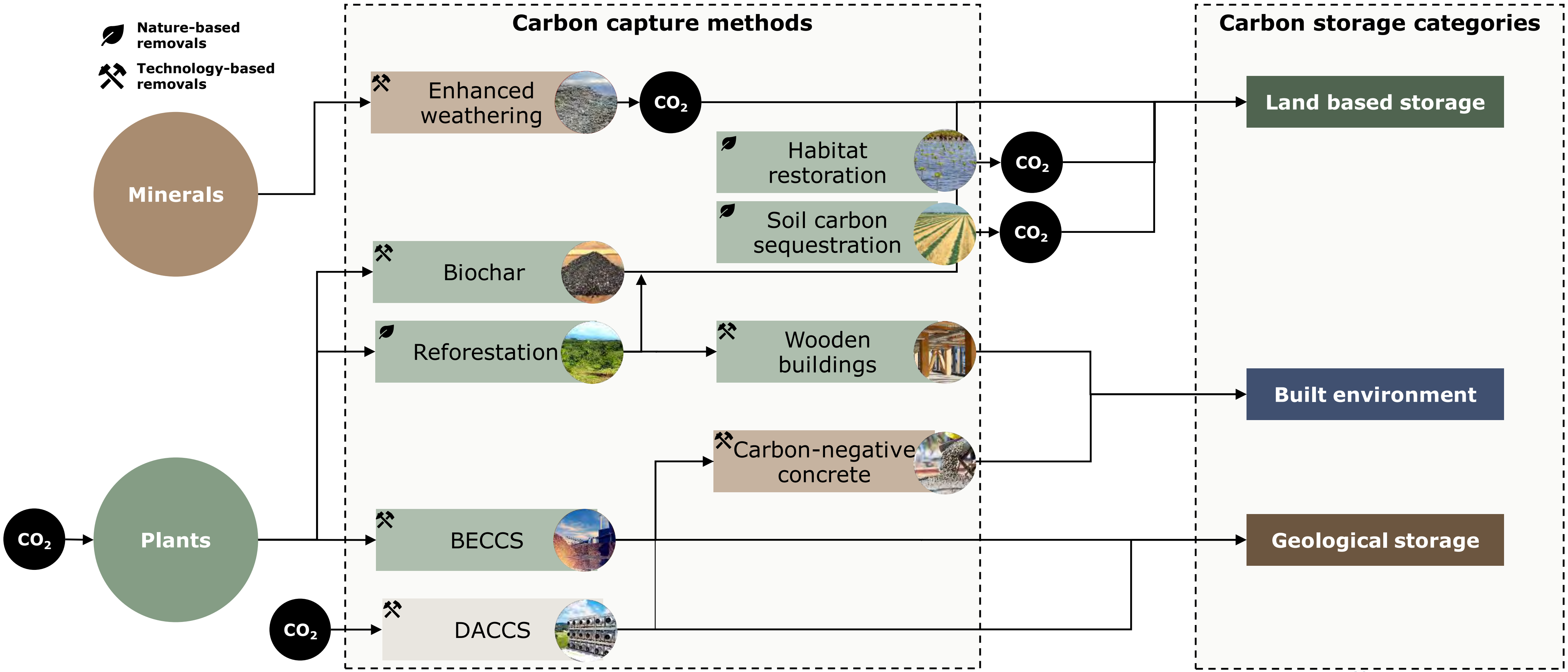
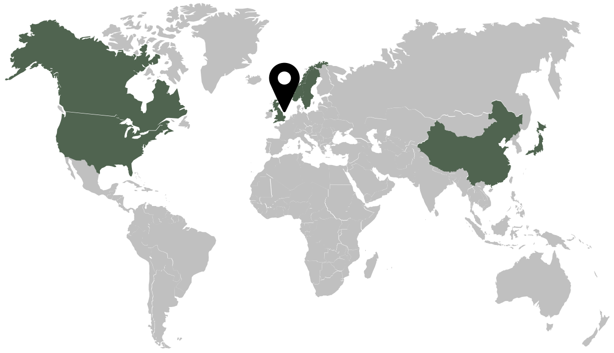



There are nine main carbon removal technologies - our focus here is on BECCS and DACCS due to the near permanent duration of geological storage



 2022-01-31 | COPYRIGHT AFRY AB | OGCI: CCUS DEPLOYMENT CHALLENGES AND OPPORTUNITIES IN THE GCC

BECCS is the most advanced technology for permanent removal



Project Example

Drax Biomass Power Station, Humber

Drax is planning to install BECCS on four biomass generating units to capture 4Mt/y of CO_2 from each unit and store in the North sea.

Project Length: 2019 – 2035 (Pilot capture in place since 2019, full scale capture on Unit 1 and transport and storage by 2027, Unit 2 by 2030 and Unit 3&4 by 2035)

Required carbon price: ~$150/t$CO_2$e

Co-benefits: Income for local, 6,000 job opportunities, worlds first BECCS

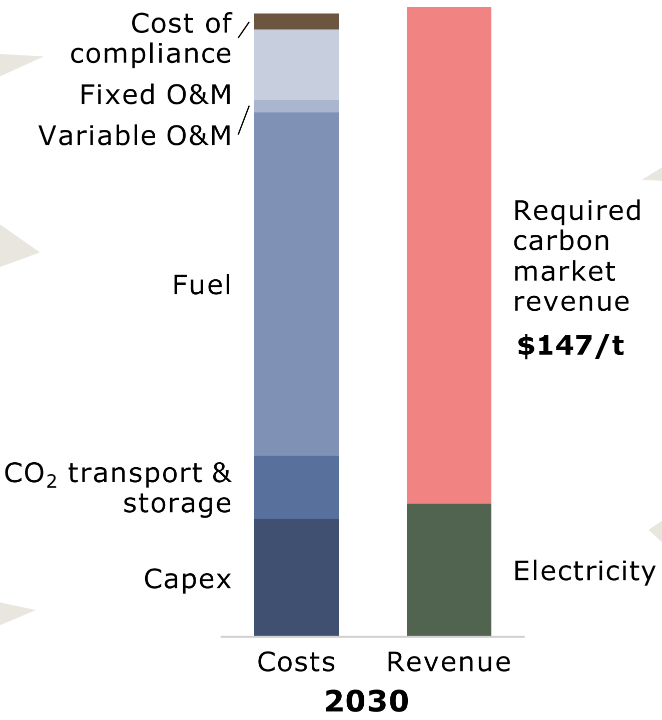
Cost of compliance
The costs associated with selling credits including MRV / insurance.

Opex
The operating costs incurred by BECCS projects are dominated by Fuel, CO_2 transport & storage and O&M costs.

Capex
Levelised capital costs incurred by the project

COSTS AND REVENUES ($/t)

Indicative Coal to BECCS Conversion



Carbon revenue

The required carbon price to make the project profitable

Revenue streams

Revenue streams available to the carbon removal technology including anticipated level of government subsidy.

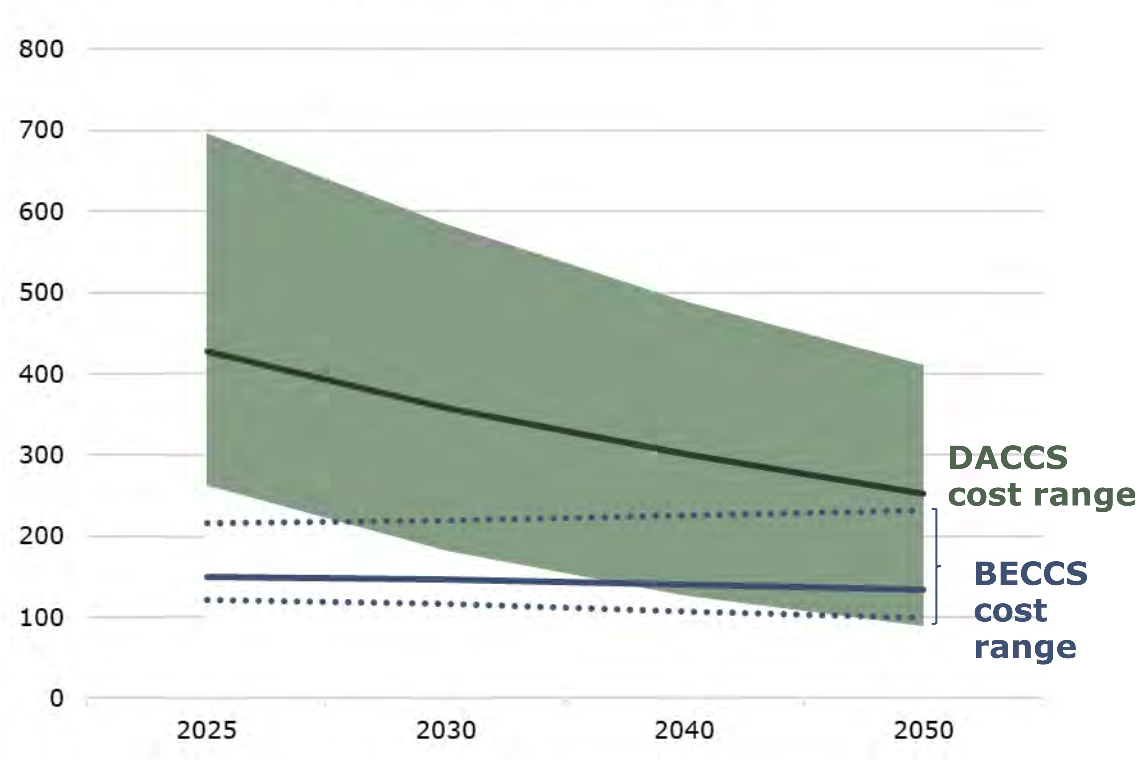
The various revenue streams available to the removal technology

BECCS analysis is provided here principally to show how it compares with DACCS costs, rather than advocating for BECCS in the GCC. For BECCS in the GCC, agricultural waste via direct combustion or via Renewable Natural Gas (RNG) could be used as the feedstock, rather than wood pellets which are the typical global feedstock.

BECCS is projected to deliver cheaper removal in the short-term, but BECCS faces major sustainability concerns

LEVELIZED COST OF REMOVAL IN NORTHERN HEMISPHERE: DACCS VS BECCS

$/tCO$_2$, real 2020 money



[1] BECCS-deployment: a reality check. Imperial College London, January 2019

COMMENTARY

Costs are highly uncertain

- Our outlook is based on our in house engineering team, academic literature, and aspirational targets published by project developers
- Cost reduction is likely to be a function of deployment for DACCS; for BECCS, whilst capex is expected to decline over time, fuel costs and electricity prices will vary

Cost is not the only factor

- BECCS is facing resistance from NGOs and academics
- For the 1.5°C target, CO_2 removal by BECCS has been evaluated to >20Gt of CO_2 per year by 2100. This massive deployment of BECCS would require between 0.4 and 1.2 billion hectares of land (25% to 80% of current global cropland[1])

Northern hemisphere costs

- These costs represent an outlook for the northern hemisphere; next we'll see how DACCS costs in the GCC region compare

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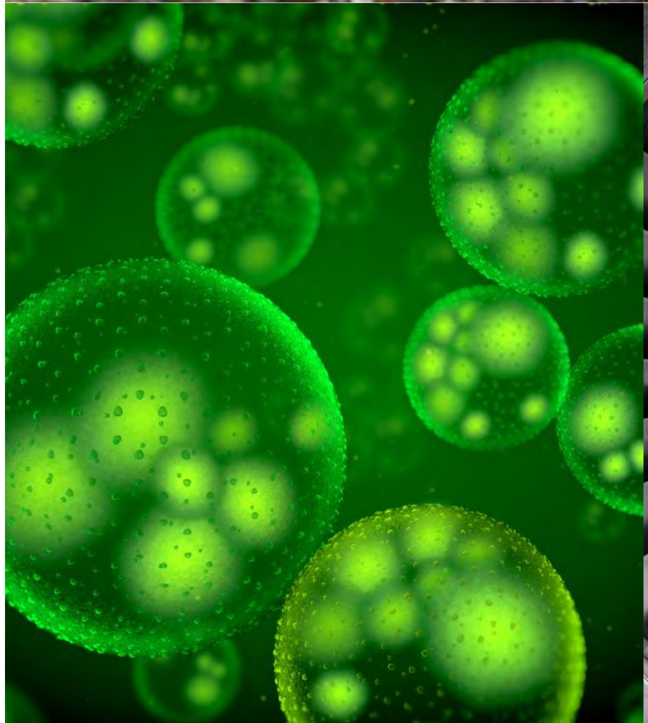
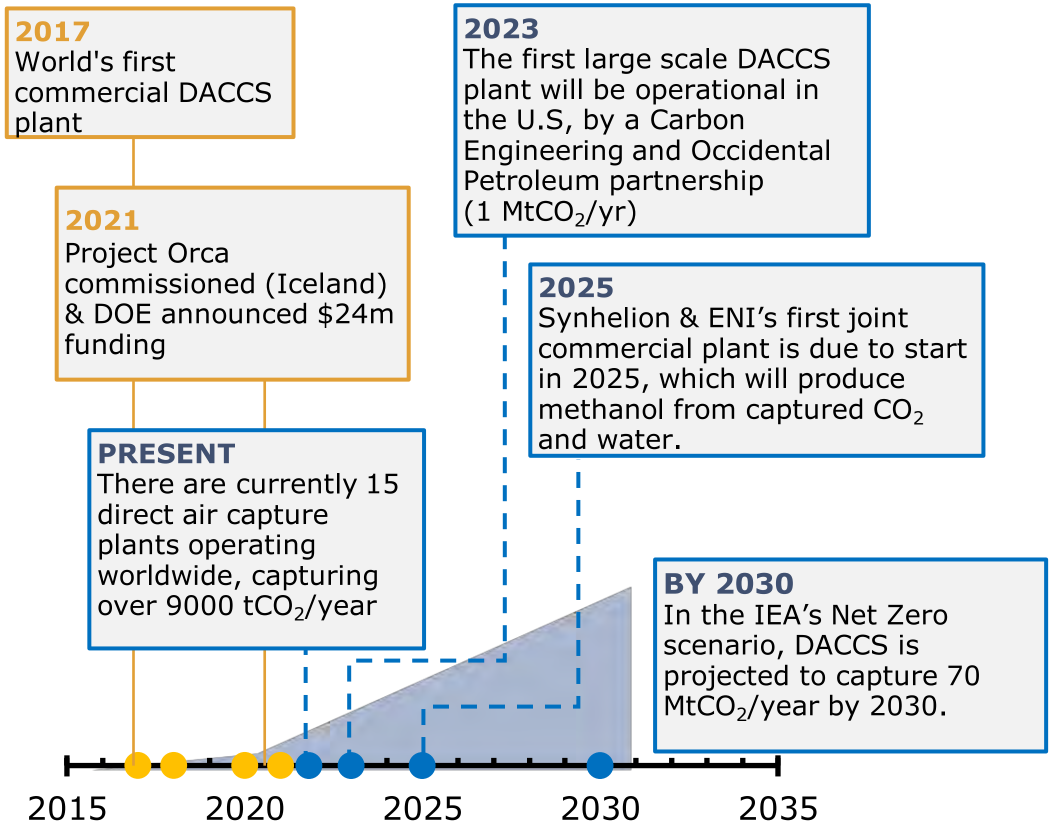
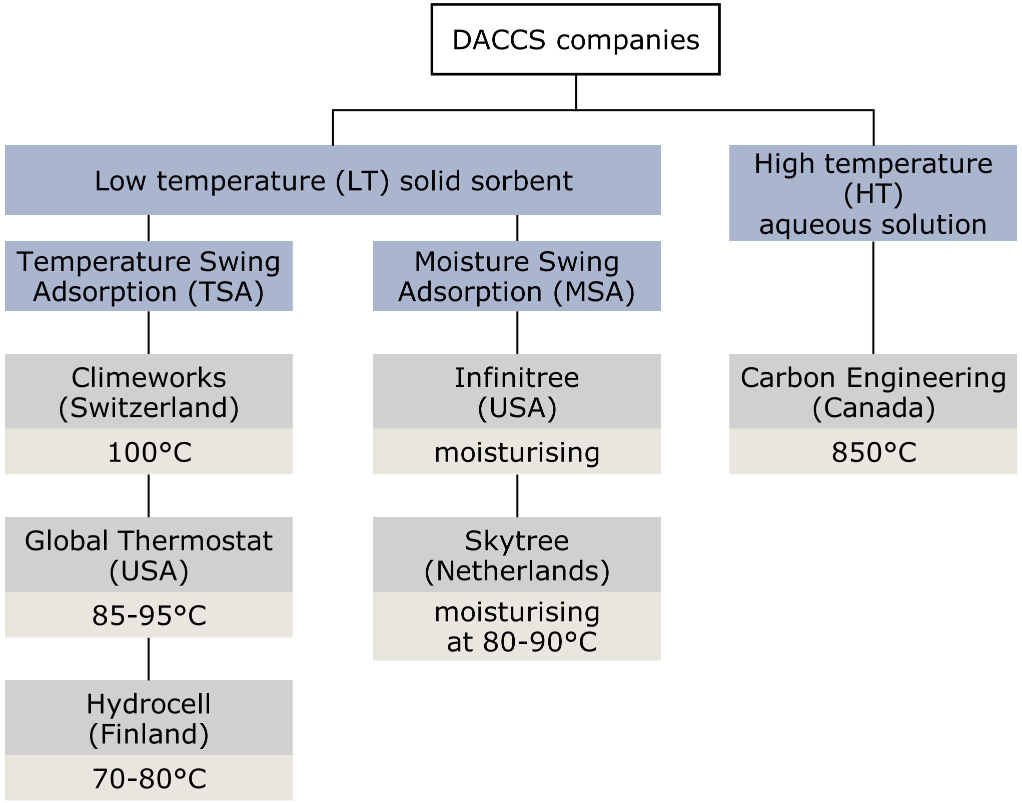


DACCS technologies are in the early stages of commercial development

DACCS SCALE-UP



TECHNOLOGIES USED BY DACCS COMPANIES



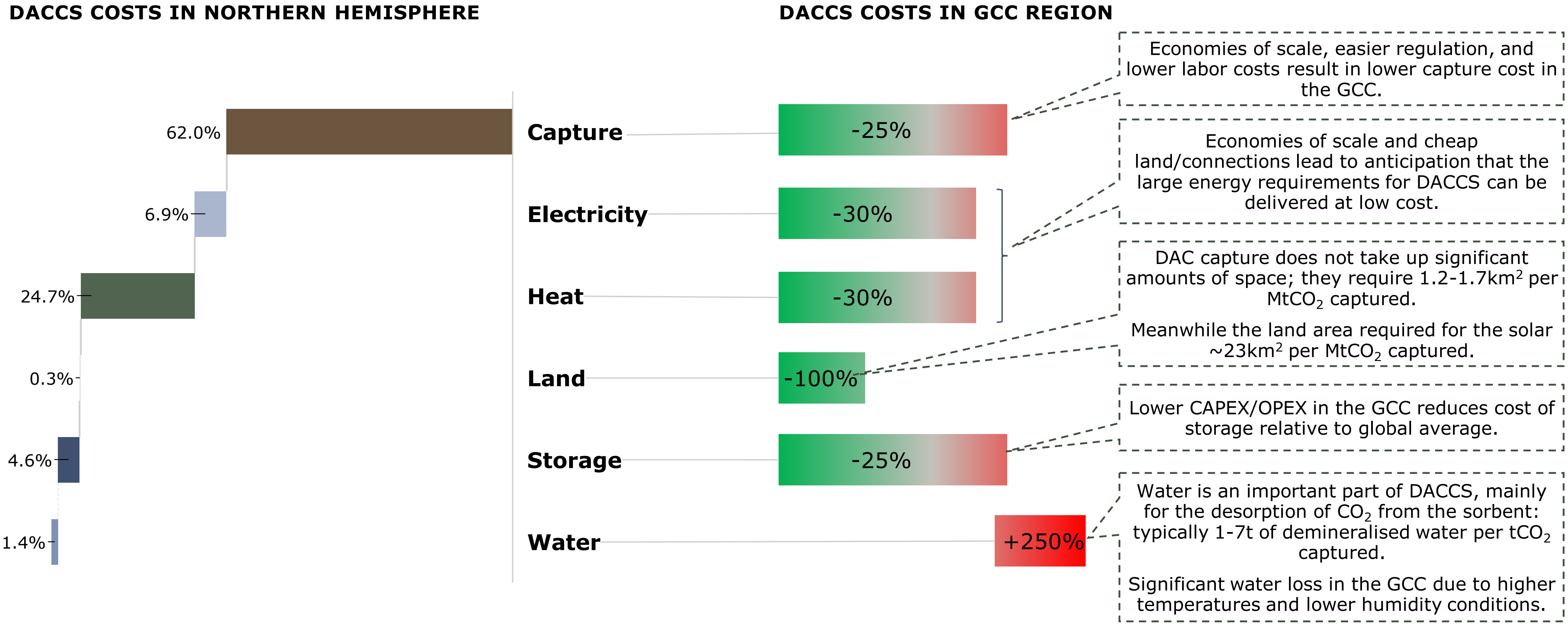
Low temperature DACCS systems have less resource requirements

	Low temperature[1]	High temperature
	globalthermostat (a carbon negative solution); CLIMEWORKS	Carbon Engineering
Technology	Adsorption and desorption: CO_2 is bound to a solid sorbent via organic-chemical adsorption and then released by low temperature heat (**ca. 100°C**)	Absorption and calcination: CO_2 is absorbed as an **aqueous solution** and released through calcination under temperatures of **>850°C**
Energy supply	Low temperature intensity allows the utilization of waste heat, energy sufficient heat pumps and RES provided heat leading to a CO_2 **capture rate of 90%**	High-grade heat demand currently requires natural gas as energy demand leading to **0.5 tons CO_2 emission per captured ton**
Water demand	Highly dependent on location of the plant. In Iceland water is as a **by-product from moisture** in the ambient air, 1 m^3 per captured ton CO_2 **produced**	Water is constantly introduced to the system due to **net water losses** following vaporization in the heating process, 4.7 m^3 per captured ton CO_2 **used**
Specifications	Climeworks: Amine as adsorbent, time of full regeneration cycle **4 - 6 h**, CO_2 purity **99.9%** Global Thermostat: Amino-polymer as adsorbent, separated units for ad/-desorption, time of full regeneration cycle **30 min.**, CO_2 purity **>98.5%**	Potassium hydroxide (KOH) as solvent, separated units for absorption and calcination, **no regeneration time** since processes run simultaneously, CO_2 purity **>97.1%**

1 Referred to Temperature Swing Adsorption (TSA), most commercialized low temperature DACCS system

Gaffney Cline AFRY ÅF PÖYRY

DACCS cost is dependent on access to cheap finance, energy, carbon storage, and water

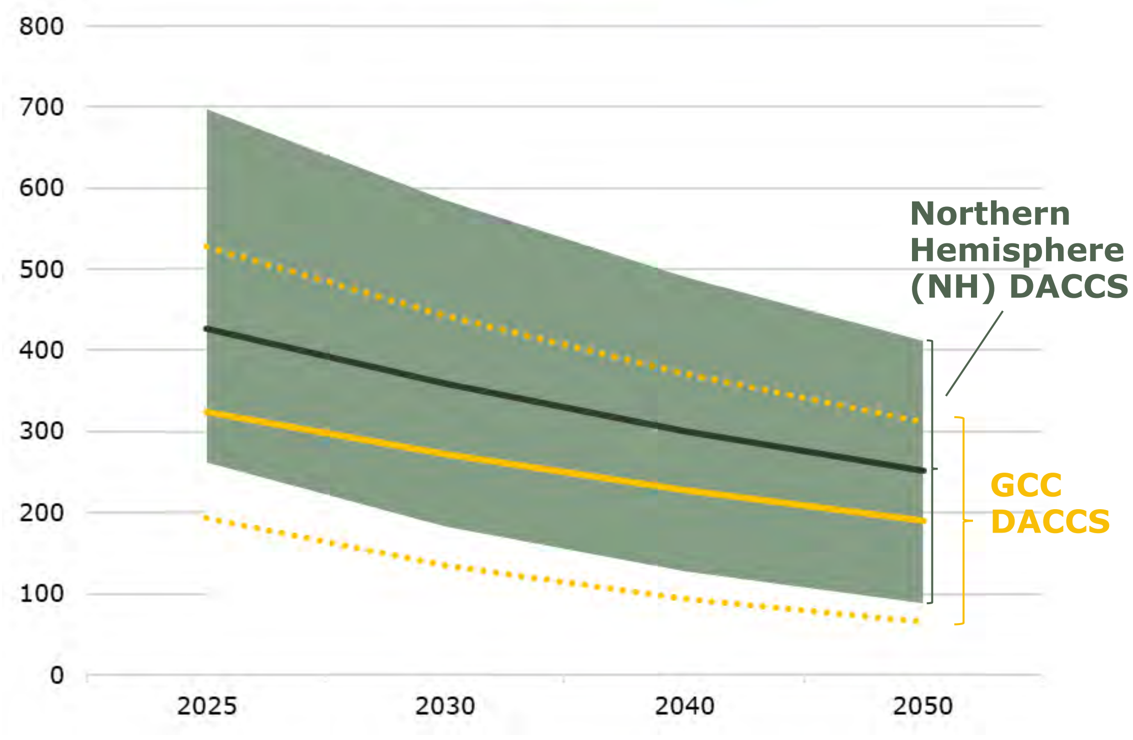


For a low-temperature TSA system

DACCS could be cheaper in the GCC region, providing water requirements can be met

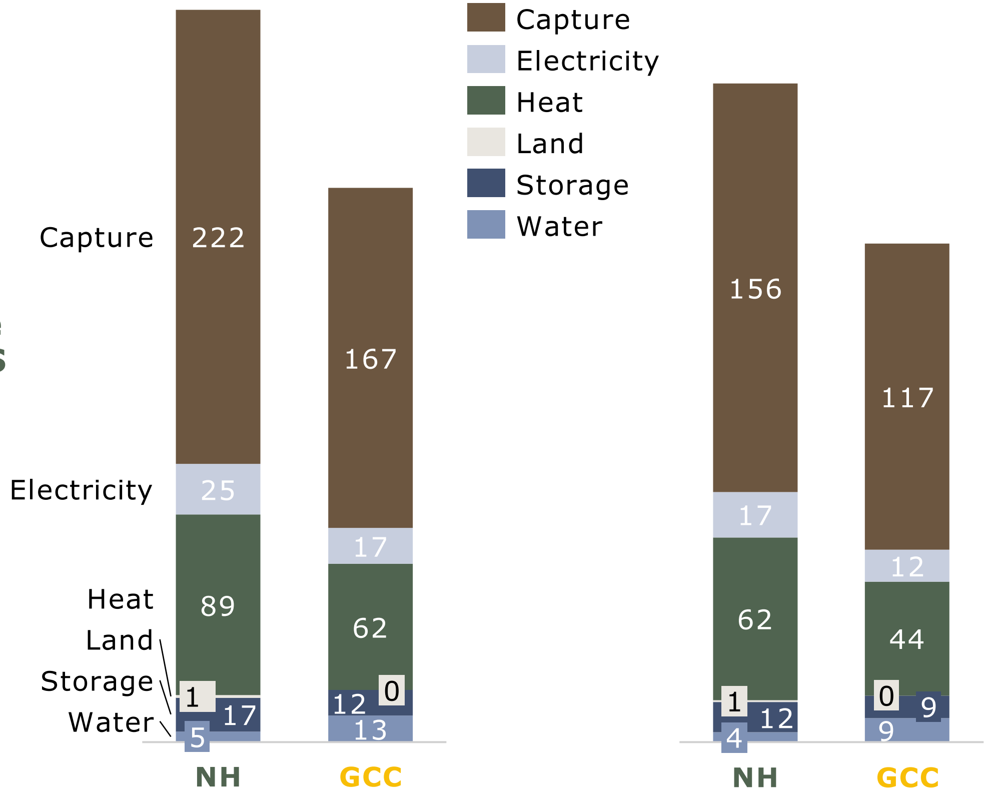
LEVELIZED COST OF DACCS: NH[1] VS GCC

$/tCO$_2$, real 2020 money



BREAKDOWN BY COMPONENT (BASE CASE)

$/tCO$_2$, real 2020 money



[1] NH: Northern Hemisphere

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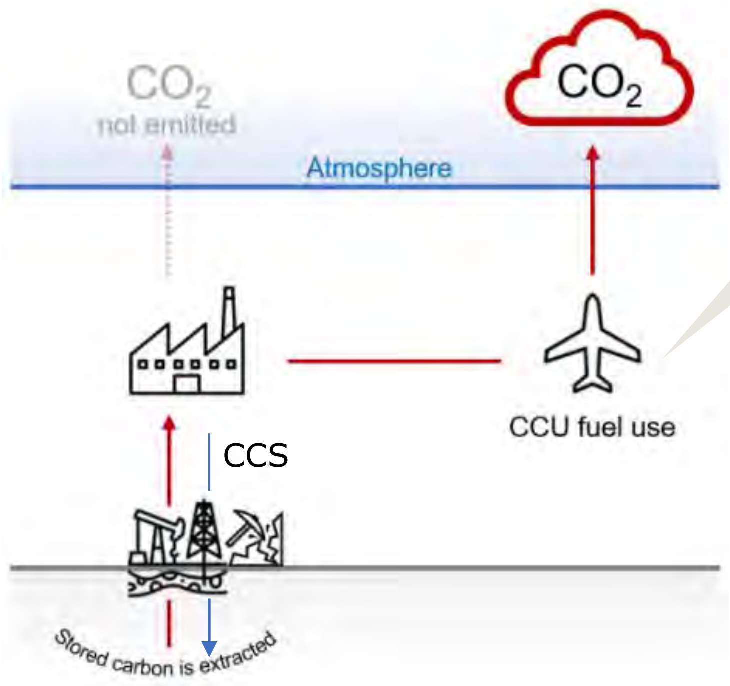
DAC carbon can be used to make a carbon neutral e-fuel

CCS + SYNTHETIC FUEL

- CO_2 captured fossil fuel combustion
- CO_2 captured < CO_2 emitted

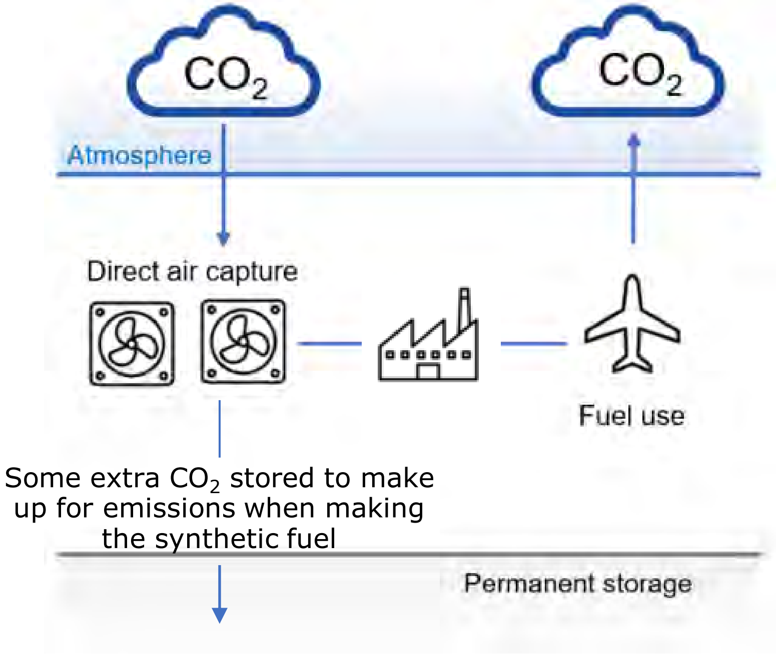
Low-carbon (rather than carbon neutral) fuel as not all the fossil CO_2 emitted in production can be captured



DAC + SYNTHETIC FUEL

- CO_2 captured from atmosphere
- CO_2 captured = CO_2 emitted

Carbon neutral

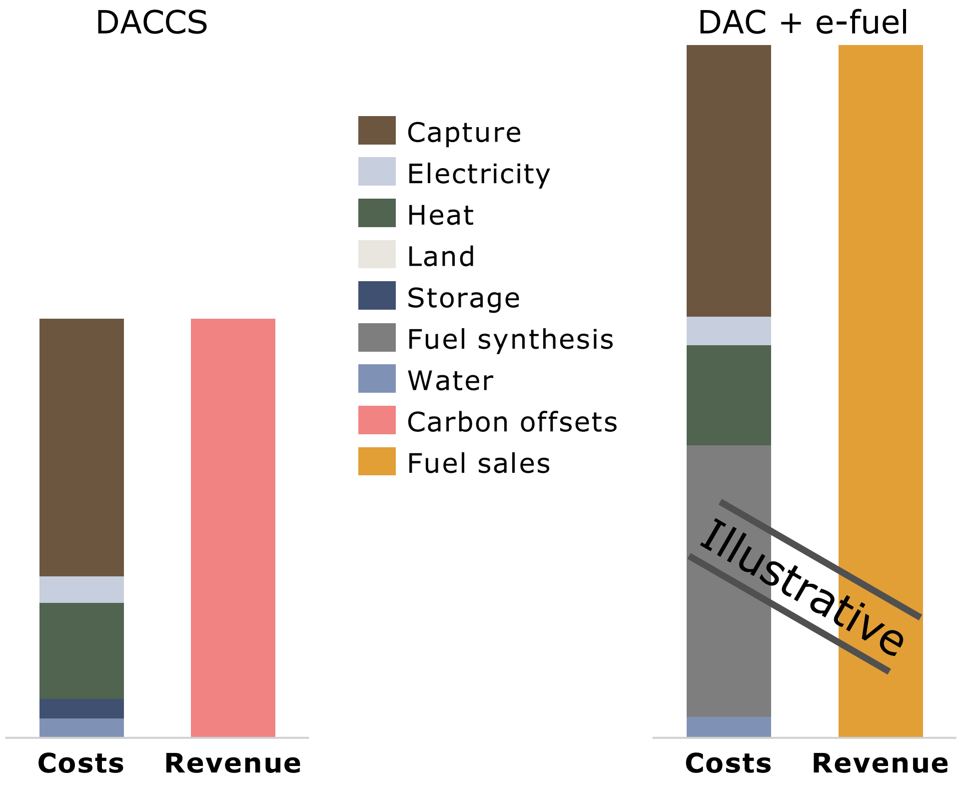


Source for figures: Bellona Foundation with AFRY modifications

The economics of e-fuels are based on those of DACCS, albeit with likely higher costs and revenues

ILLUSTRATIVE COSTS & REVENUES

$/tCO$_2$ captured



COMMENTARY

Economics

- For e-fuel production:
  - the storage component of the DACCS cost is replaced by the cost of fuel synthesis; and
  - revenue now comes from the sale of the e-fuel rather than the sale of carbon removal offsets
  - 100% of the revenue from the DAC and e-fuel model comes from fuel sales (we assume zero contribution from offsets)

Competition

- e-fuels are in competition with biofuels, but biofuels face higher sustainability challenges compared to e-fuels from DACCS
- This is similar to the way DACCS competes with BECCS (albeit biofuels are likely to go through a direct chemical route so their cost structure is different)

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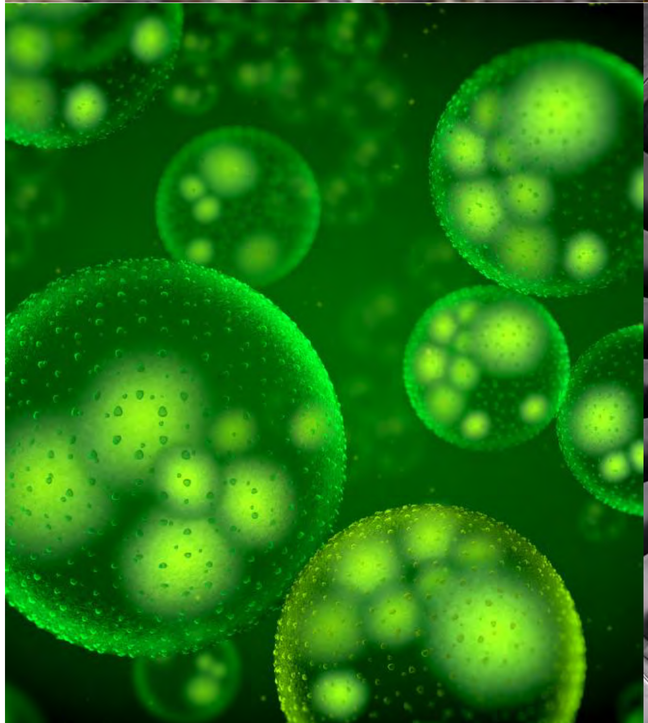
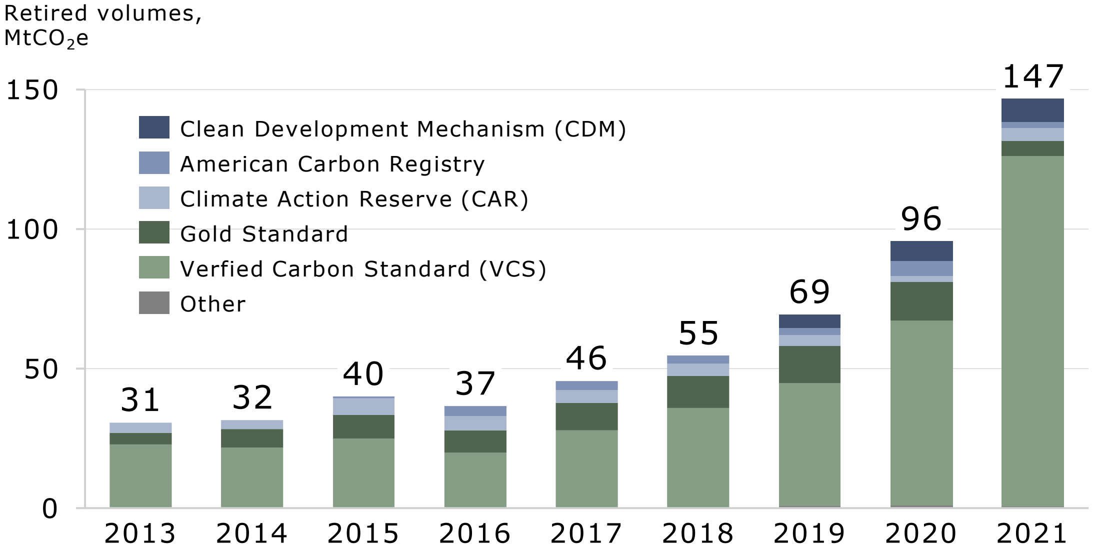


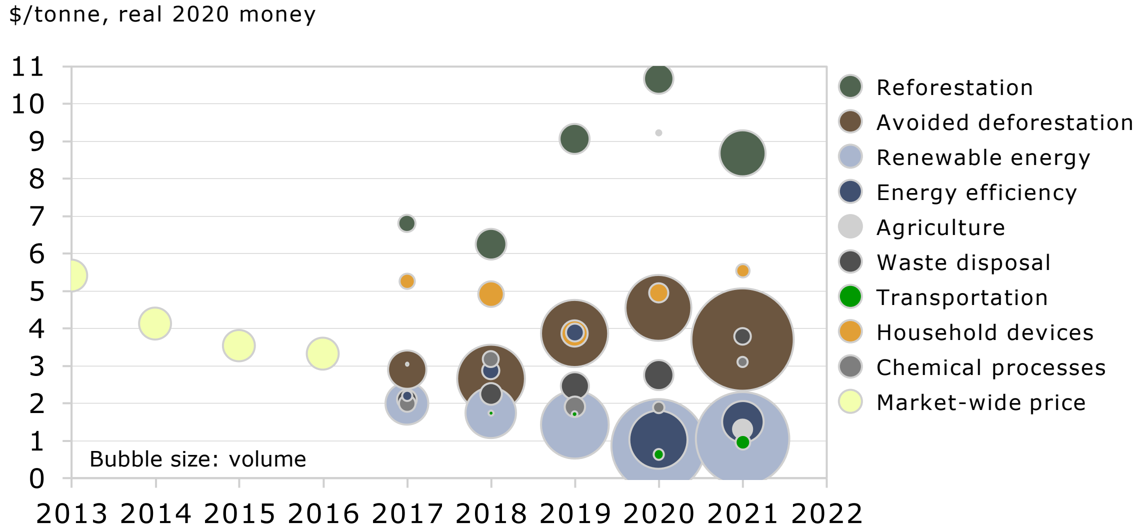

The voluntary offset market comprises of four large standards; offsets trade at prices significantly below the major compliance markets

HISTORIC VOLUMES BY STANDARD ORGANISATION



- The four large standards are: Verified Carbon Standard (VCS), Gold Standard, Climate Action Reserve (CAR), and American Carbon Registry*.
- The market is growing significantly with a retired volumes doubling from 2019 to 2021.
- Increased corporate awareness for net zero commitments has increased the demand for offsets, but supply continues to outstrip demand meaning despite the surge in volume, prices have remained relatively constant.

HISTORIC PRICES BY TECHNOLOGY

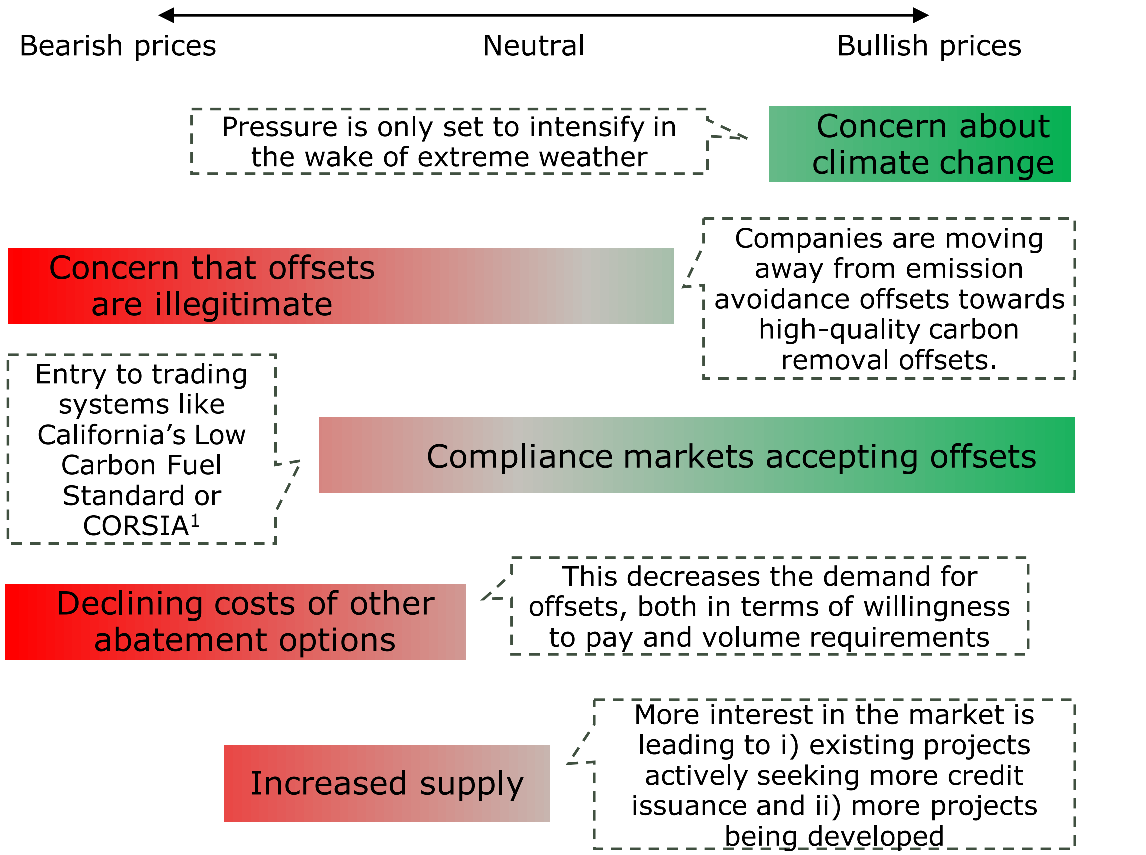


- Offset prices are low but there is a price premium for carbon removal offsets.
- Reforestation is the only project type that can remove carbon from the atmosphere at large-scale.
- Technological methods for carbon removal are in their infancy, but are starting to generate high prices e.g. biochar offsets are selling for >$30/tonne (not shown in chart as volumes are currently very small).

*Clean Development Mechanism is also large but is mainly used for compliance purposes. Source: Ecosystem Marketplace; 2021 data up to 31 August 2021

Supply and demand for offsets are both set to increase leading to a stable price outlook for high-volume technologies

PRICE DRIVERS



OTHER DEVELOPMENTS ON WATCH

- Taskforce for Scaling Voluntary Carbon Markets (TSVCM):
  - The TSVCM is trying to scale the market by 15-fold by 2030. It is in the process of defining which technologies, methodologies, vintages, and other attributes should be considered eligible for their 'Core Carbon Principles' label.
  - This will bring further segmentation to the market. We are likely to see low demand for non-CCP eligible offsets, medium demand for CCP-eligible offsets, and high-demand for carbon-removal offsets.
- Article 6 of the UNFCCC Process:
  - Wherever two parties are engaging on a voluntary basis in the use of internationally transferred mitigation outcomes it is crucial to avoid double counting of carbon mitigation actions between Nationally Determined Contributions (NDCs) and voluntary offsets in the private sector.
  - Article 6 discussions concluded at COP26 in Glasgow for bilateral transfers between nations, but implementation in the voluntary market will depend on the Standard Organisation. Gold Standard has said it will phase in the use of offsets that come with a Corresponding Adjustment to the host country's NDC, whilst VCS has reported that they will not.

[1] Carbon Offsetting and Reduction Scheme for International Aviation

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CHAPTER 10

Roadmap for deployment of CCUS in the GCC

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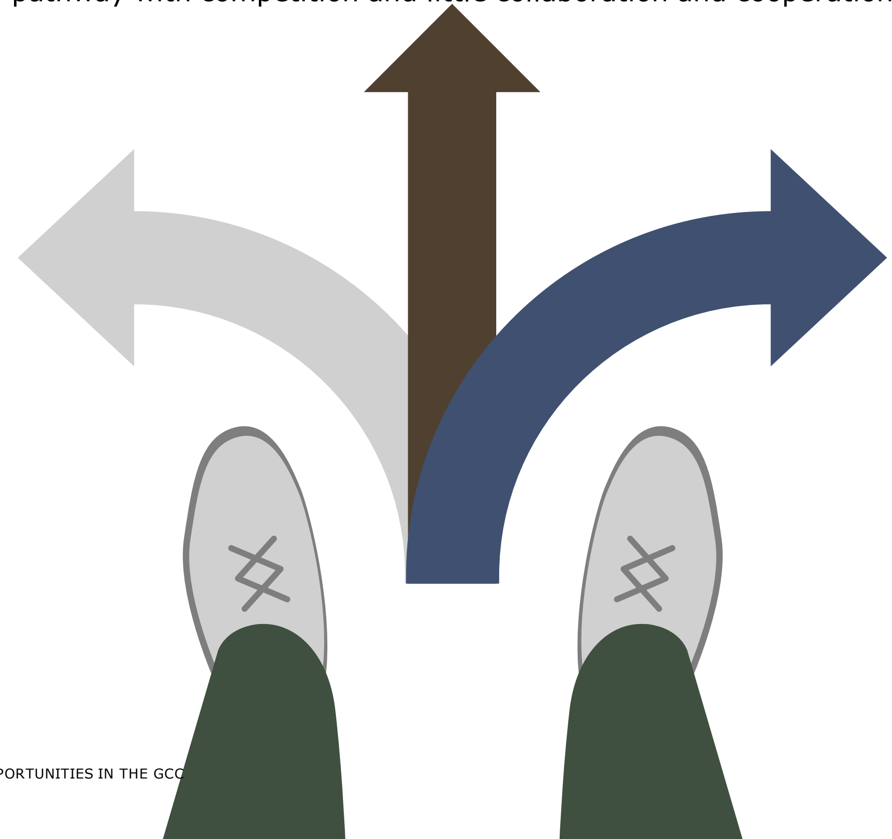
The GCC is currently at a crossroads with CCUS deployment and will need to make a decision which route will meet most policy aims

The Status Quo

In this scenario the GCC favours long term oil and gas production over decarbonisation efforts. Whilst pilot projects will be carried out by both private and state companies there is not the political will to accelerate the deployment of CCUS in the GCC. States follow their own decarbonisation pathway with competition and little collaboration and cooperation

Fast Follower

In this scenario the GCC prepares for decarbonisation but does not lead it, waiting for dominant technologies to emerge. The expertise of the region allows it to catch up but at the cost of market share, particularly in hydrogen. The region becomes a world class hub for CCUS, which allows the export of low carbon products and fuels



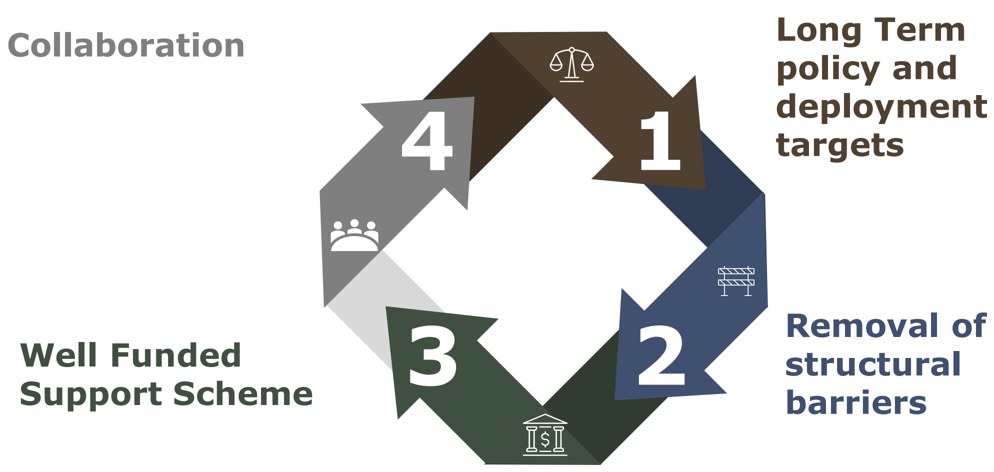
Global Leader

The GCC takes the lead on decarbonisation domestically and seizes the opportunity in CCUS and hydrogen, dominating the market for low carbon products and supplying hydrogen to Europe and Asia. R&D into pyrolysis generates a new market for solid carbon products and industry in the region. The GCC is able to export its knowledge and expertise to other countries and becomes a global hub for hydrogen and CCUS

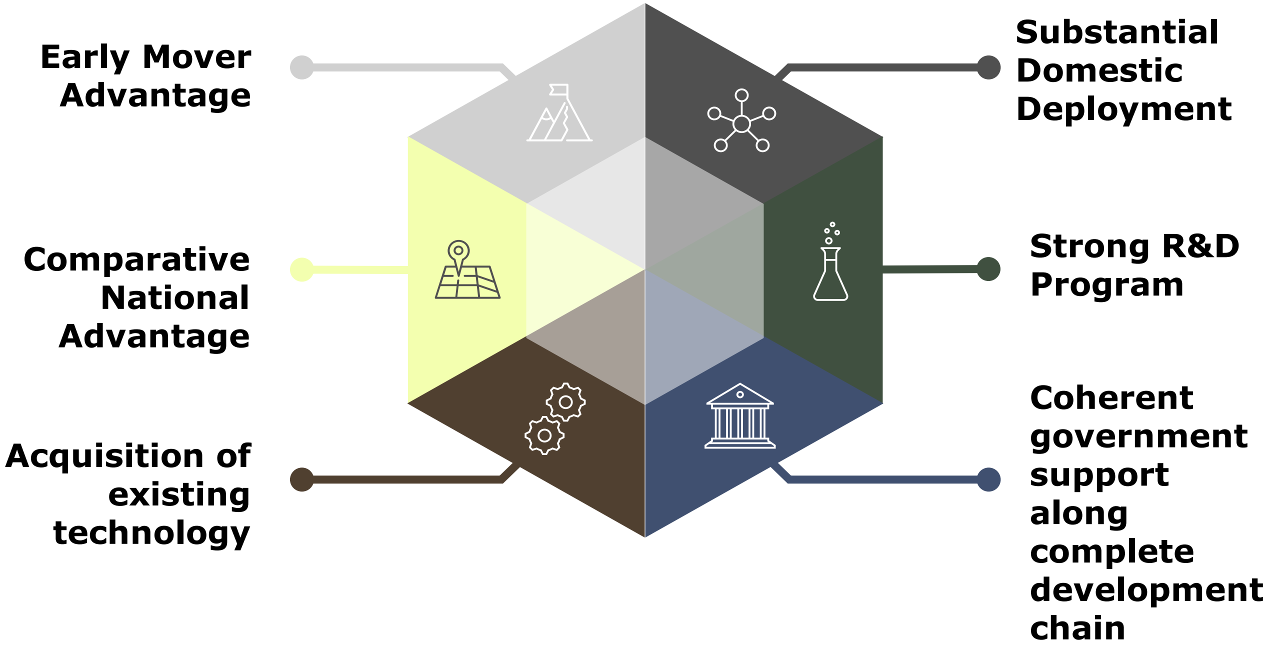
Successful development of CCUS and hydrogen is predicated by a consistent and substantial deployment programme

– This roadmap has been prepared for the OGCI and sets out the steps necessary for establishing a substantial programme for deployment of CCUS and hydrogen as a route to meet net zero targets in the GCC. In developing this CCUS and hydrogen roadmap for the GCC we have drawn extensively on the experience of other countries to learn the lessons behind the successful early adoption of these technologies, which is summarized below.

Development



Deployment



External factors identified via a STEEP analysis inform the framework for a workable deployment roadmap

SOCIAL

Suspicion of o&g states commitment to decarbonise

Opportunity for job creation and new industries

General appetite for risk and new ventures

TECHNICAL

Immaturity of technology

R&D to accelerate beneficial tech such as pyrolysis

Effect of CCUS on existing operations

Potential failure of storage sites

ECONOMIC

Carbon border taxes

Huge revenues from existing o&g production

Current high cost of technology

Lack of a GCC carbon price

Opposition to subsidy

Opportunity for economic diversification

Potential failure in value chain

ECOLOGICAL

Meet Paris targets

Environmental impact of CCUS and DACCS components

Pressure on already fragile hydrological systems

POLITICAL

Government comfort with status quo

Collaboration versus competition

International consensus on decarbonisation journey

Policy support to expand available volumes (subsidy & incentive)

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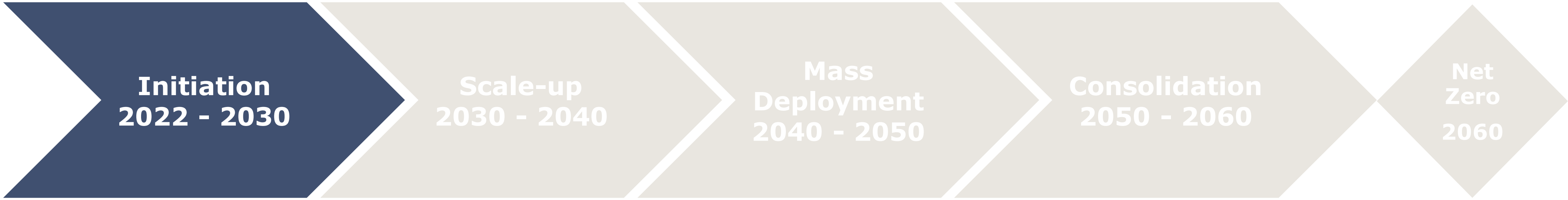
The roadmap for deployment consists of four phases starting with Initiation to frame actions in the early 2020’s



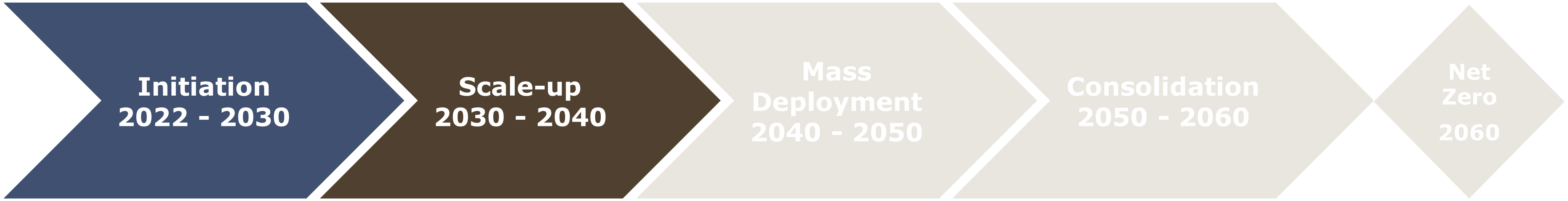
– **The Initiation Phase** – The purpose of the initiation phase is to carry out the initial deployment, research and planning activities necessary to ensure CCUS is delivered cost-effectively in the scale up and mass deployment phases. In the initiation phase, critical evidence is gathered to support policy decisions, research and technology development are completed to underpin domestic CCUS, engineering design work is begun and the funding needed for scale up is allocated.

– Detailed CO_2 storage appraisal across the GCC is the first step to realise any value from CCUS, which must include delineation of individual stores and associated volumes. At the same time there should be an in-country policy review to ensure barriers are removed for large scale deployment of CCUS and hydrogen. The first steps to coordinate and collaborate across borders should also be undertaken to ensure that standards and policies can enable cooperation later.

– An inventory of industries and decarbonisation pathways for those industries should both inform policy and support research activity, which will need to focus on capture technologies and utilisation. The large hydrocarbon economies of the GCC also support research into emerging oil to hydrogen technology and the pyrolysis process, which produces hydrogen without CO_2

– Markets research and infrastructure plans for a CO_2 backbone both in country and across the GCC should be completed by 2025, so that early projects and the first hub can be brought online by 2030.

From 2030 onwards scale-up envisions growth and development of the CCUS industry in the GCC around three hubs

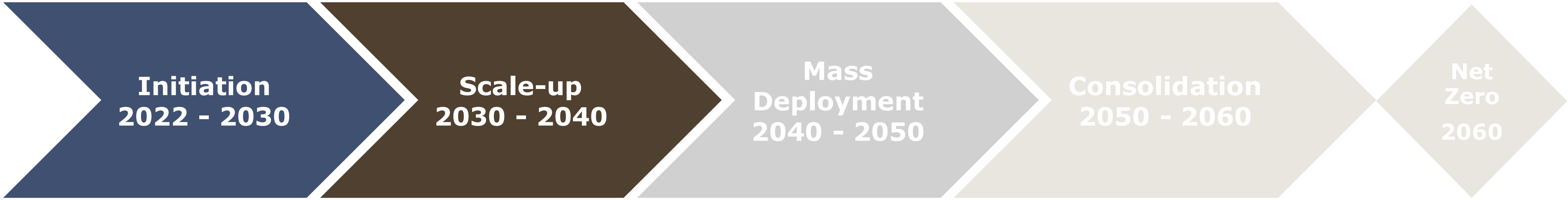


- **The Scale-up Phase** – The aim of the scale-up phase is to develop early commercial scale CCUS projects and build out T&S infrastructure to facilitate the mass deployment phase. At the same time, policymakers should develop and implement funding mechanisms aligned to GCC economic policy, monitor the progress of cost reductions, evaluate the efficacy of subsidy and incentive schemes and continue to assess the business case for CCUS in preparation for the roll out phase.

- Expansion of hubs and the tie in of additional clusters is the key part of this phase both in number and diversity. The GCC should be targeting 3 hubs by 2035, which should now include a full suite of industries to drive down the cost reduction curve. Initial roll-out of CCUS has required the revenue streams from EOR to support the business case, however broader support will be needed to support scaling up. This will require government subsidy and support mechanisms to encourage switching to CCUS and hydrogen. Market reforms such as a carbon price, emissions trading etc. will be required for cost effective delivery of CCUS. Research focussing on carbon transport and carbon capture as a service (CCaaS) should also be part of this phase.

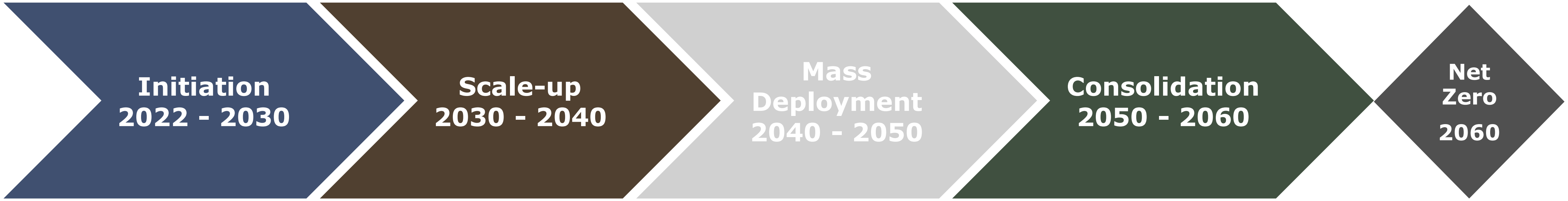
- By 2035 it would be expected that gas processing, hydrogen, ammonia and methanol would be fully decarbonised to allow for the export of low carbon products. These easier to abate sectors will act as a bell weather on progress not just in the GCC but globally as the clock runs down on countries net zero targets. BECCS and DACCS should also begin pilot deployment in order to maintain the ability of the GCC to export oil and gas as higher carbon producers are sidelined.

From 2040 mass deployment of CCUS technology should take advantage of the established infrastructure and allow for imports of CO_2



- **The Mass Deployment Phase** – The purpose of the mass deployment phase is to build sufficient track record to access capital at reasonable market rates, and to build up a sustained CCUS industry supply chain capable of delivering sufficient installation rates. During this phase, an ongoing review of the funding mechanism will ensure it continues to deliver value for money. Towards the latter end of this phase, domestic CCUS is consolidated as a mature industry.
- By this stage it would be expected that the policy, fiscal and regulatory framework is stable and only minor tweaks would be expected to reflect changes of targets and/or strategy. As DACCS begins to be rolled out a support mechanism for ‘carbon scrubbing’ will need to be developed which will evolve to cover the remaining sectors that cannot be decarbonized.
- As technology evolves it is expected that harder to abate sectors will become cost effective to develop leading to additional hubs in the GCC and likely smaller clusters that will feed into hubs. With an established CO_2 backbone streams can be directed to use and storage as appropriate and a regional CCUS and hydrogen corridor will emerge . It is in this phase that the system is likely to be able to handle imports from regional neighbours with less favourable geology. As such the framework for CCaaS will need to be developed.
- Globally oil and gas demand will be falling, provided countries are sticking to their pledges and it would be expected that oil and gas production would be switched to hydrogen (if the research and economics supports this)

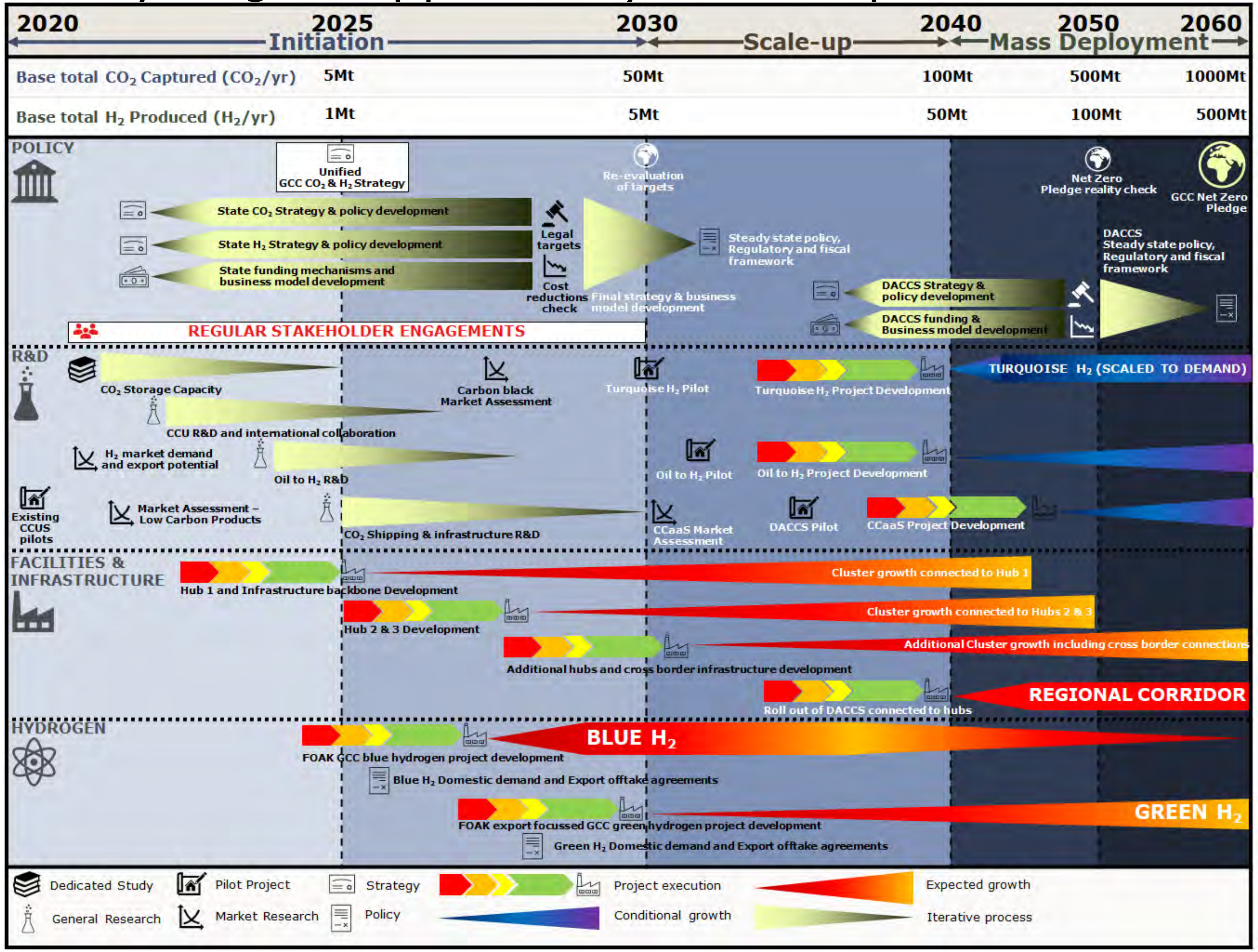
As the industry is consolidated and becomes mature all remaining emissions will have to be addressed by elimination or DACCS to reach Net Zero



- **The Consolidation Phase** – Domestic CCUS is consolidated as a mature industry and is a matter of course for all new industry. Additional CCUS hubs and clusters are expected to be much smaller but all will tie in to the regional GCC CCUS ecosystem. By this stage all but the impossible to abate sectors will be part of this ecosystem and the remaining emissions will need to be eliminated, or abated by DACCS.

- **The Net Zero Phase** – The ultimate endgame for the roadmap is the milestone of Net Zero, but this phase represents that target and beyond with the expectation that deployment and technology will move towards negative emissions. For the GCC this is targeted for 2060 at the present time (although some states have earlier targets). The Net Zero date is important to bear in mind as this roadmap unfolds as movement to an earlier date will require acceleration of activities. By Net Zero all CO_2 emissions will have been eliminated, substituted or abated. Renewables, battery storage and hydrogen are expected to be the dominant energy vectors both in the GCC and globally.

The GCC CCUS & Hydrogen Opportunity Roadmap to 2060



The roadmap should be considered as a guide with the flexibility to adapt to changing realities and global progress to net zero

COMMENTARY

- The opportunity roadmap takes a fairly conservative approach reflecting a fairly steady path to decarbonisation and support for continuing oil and gas production in the GCC
- One of the first decisions for the GCC is to agree on the pace of the transition and whether the GCC wants to be a global leader in CCUS technology and deployment, as well as hydrogen
- The conditions and opportunities as detailed by this report show that there is scope for the GCC to take the lead but it is possible to delay progress at the cost of market share as other regions (particularly North Africa and Australia for hydrogen and NW Europe and North America for CCUS) forge ahead with their plans
- There is also the issue of cost – whilst being a fast follower will lead to lower costs for individual project deployment the timescale will be compressed meaning more CAPEX spend on an annual basis to keep to the net zero target
- Arguably, acting sooner and being a leader will mean lower annual costs which are also ‘insured’ by current oil and gas revenues

CAVEATS

- As with all strategies and roadmaps, the need for internal reflection and sense checking will be critical and as such the overall process has the opportunity to be adapted to changing circumstances
- This is particularly true in project execution where learnings from previous projects and global knowledge sharing will likely reduce the FEED, DE (Detailed Engineering) and execution timescales
- The opportunity for hydrogen is also likely to be very fluid with widely differing views on the rate of market growth and the source of hydrogen (whether green, or low carbon; as hydrogen, or a derivative, such as ammonia)
- The pace for CCUS itself is likely to be dictated by individual countries within their own pledges for decarbonisation – however large markets such as the EU are looking to encourage decarbonisation with policies that would disadvantage a range of exports from countries that are lagging compared to the overall global progress
- The pace of decarbonisation globally is still very much unknown given its link to economics and politics, but it will have to be faced eventually and delays will cost more

The initiation pathway to 2030 is all about policy, partnership and pilots and a heavy focus on domestic roll out

2022

Initiation

Kick-off of CO_2 storage catalogue across GCC and launch of in country policy reviews for CCUS and hydrogen. Workshops should be held to align GCC stakeholders and agree what vision for CCUS to follow

2024

First of a kind

Storage studies should be concluded and proximity to sources ascertained. The next step is to design the plumbing to connect source and sink. The GCC should have identified a pilot hub(s) for pre-FEED and FEED. Cross border policy with regard to CCUS and hydrogen should be considered to allow a connected infrastructure ecosystem

2026

Early domestic growth

Policies for CCUS and hydrogen should now be in place to cover domestic requirements, cross border initiatives and import/export. The first hub(s) should be operational and looking to expansion to cover more industries. R&D on capture technologies starts to bring down the cost for CCUS and domestic hydrogen production begins to decarbonise gas processing and existing grey hydrogen production

2030

Scale-up

With immediate domestic demand met, large scale hydrogen export is possible and associated infrastructure is built. New power is either renewable or attached to CCUS and liquids use has been phased out. CCUS and hydrogen also allows for the export of blue and green ammonia, methanol and steel

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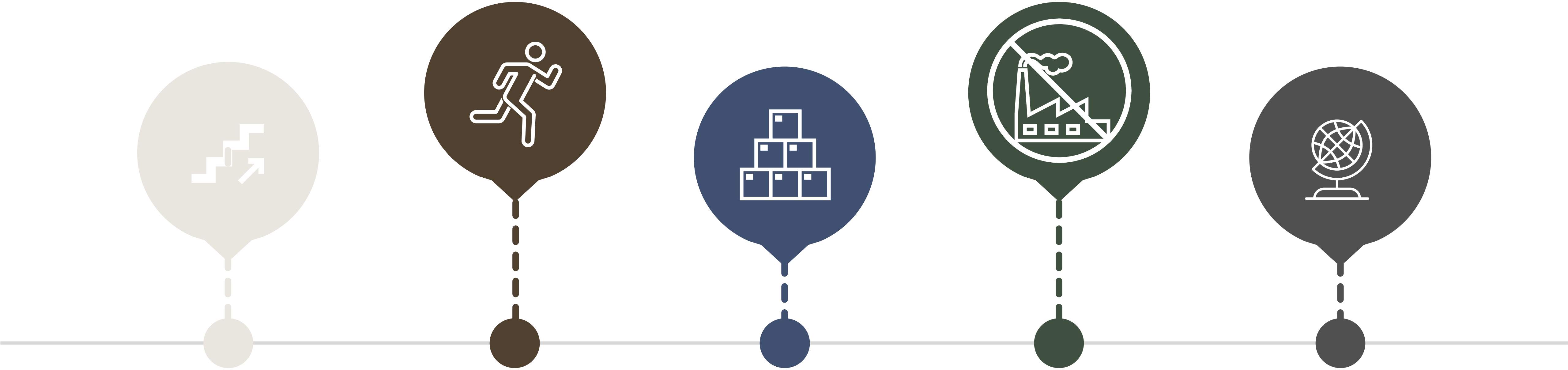
Beyond 2030 rapid scale-up is needed to unlock mass deployment from 2040 onwards, before consolidation, reaching net zero by 2060



2030

Scale-up of CCUS, export of hydrogen at scale and development of low carbon products for export

2035

Increasing pace of scale-up and connection of new hubs and sectors. All hydrogen production and natural gas processing should be blue or green

2040

All power should now be renewable or connected to CCUS. All steel, cement and refining should be green or blue, with progress in industrial heat

2050

Remaining hard to abate sectors connected to CCUS. Clear pathway to zero for all remaining sectors that can abate, with DACCS for the rest

2060

By this date all GCC countries have achieved their CCUS targets as part of their net-zero pledges. Remaining emissions will be addressed by DACCS

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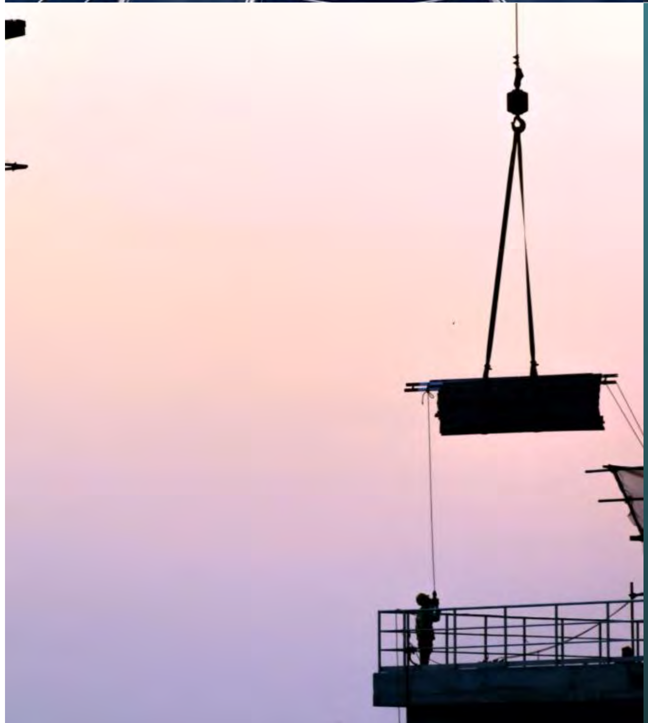



In the short term GCC countries will proceed at their own pace, but there is appetite for collaboration and a unified strategy

STATUS OF GCC PLANS

- Saudi Arabia, UAE and Qatar have taken different approaches to the opportunity presented by CCUS
- Qatar has been an early leader in embracing CCUS to decarbonise LNG and natural gas processing and has also invested abroad
- Saudi Arabia was also an early leader in decarbonisation, with the establishment of the Master Gas System to capture gas that otherwise would have been flared and is keen to take the lead in the development of CCUS hubs in the GCC region and in the global hydrogen market
- UAE has been a leader in CCUS through EOR and an early developer of grid scale renewable energy in the GCC both for power and green hydrogen. UAE is also a leader in the GCC for decarbonisation with a 2050 pledge for net zero and support for emerging technologies in CCUS and hydrogen
- Plans for CCUS in Oman, Bahrain and Kuwait are much less developed but there is a collective desire to seize the opportunities available albeit through being a fast follower both of technology and of the larger economies of the GCC

DEVELOPMENT OF THE ROADMAP

- In developing the roadmap the assumption has been that whilst the will exists to collaborate between the GCC in the path to 2030 initiatives will be on a country by country basis rather than a unified effort
- There are necessary steps that the individual countries must take in the early 2020’s to enable a more regional strategy to be developed, but it is important that there is coordination between the countries to make sure progress is equal across the GCC to enable a unified vision and collaboration on both CCUS and hydrogen
- At present this progress is not equal with Saudi Arabia and UAE forging ahead with their own visions and pilot projects as well as developed CCUS and hydrogen strategies
- Qatar too has a developed strategy linked to its leadership in LNG and decarbonisation of its natural gas and derivatives industry, but with much less focus on CCUS and hydrogen
- Plans in Oman, Bahrain and Kuwait are currently in progress and expected to catch up with the other GCC members before the end of 2023

Stakeholder engagement will be required to align strategy and also understand the barriers to deployment and the help industry needs to act

- Early in 2022 it will be necessary to bring together GCC ministries and decision makers to share their plans, vision and progress on CCUS and hydrogen. This summit should happen by March 2022.
- This first engagement should also set out the necessary steps for wider and longer term collaboration and gauge the feeling for where there are synergies and opportunities for knowledge sharing and cost reduction, it should also set out a timetable for further meetings and collaboration with a view to delivering a unified GCC strategy for CCUS and hydrogen by 2025 that the individual national strategies fit into
- In order to ensure a seamless CCUS and hydrogen market in the GCC there will need to be alignment on policies and standards, much work has already been done internationally which can be used and adapted by GCC countries and these engagements can be used to disseminate that knowledge
- Throughout the 2020’s it is also important to connect with industry and this must be done across sectors. Different industries will have different barriers to being able to deploy CCUS and hydrogen and understanding these issues will make for better policy choices. There is also a huge wealth of data and knowledge which is not shared currently and needs to be utilised. Discussing how this can be achieved and enabling knowledge sharing and collaboration will allow much more progress to be made. Separately there will need to be engagement with the NOC’s who are likely to be the owners of the transport and storage infrastructure for CCUS and hydrogen and will have separate requirements to their peers and the emissions side of their business.
- Looking more widely there is a wealth of research and projects to learn from and the GCC would do well to connect with those institutions and companies in order to understand the challenges that they have faced and how that relates to development of policy and deployment of projects. Opportunities for targeted research and collaboration are also likely to be identified under this process of engagement
- What follows are specific actions for stakeholder engagement that form the roadmap

Stakeholder engagement is important at all stages of the roadmap but particularly so in the early phases to 2030 to benefit from synergies

Initial engagements with GCC and industry to agree a path forward and shape strategy for deployment

GCC Engagement
Industry Engagement
Global Engagement
Strategy Developed

- Regional engagement with GCC ministries to agree on collaboration and unified vision
- Engagement with NOC's and industry to align government ambitions and industry and identify any barriers
- Engagement with research teams and global project developers to craft deployment strategy
- Development of individual country strategies to cover CCUS and hydrogen to form basis of further engagements to identify synergies and build a unified GCC strategy

Sharing of data and knowledge to refine strategy and allow vision to reflect individual countries competitive advantage

GCC Engagement
Global Engagement
Industry Engagement

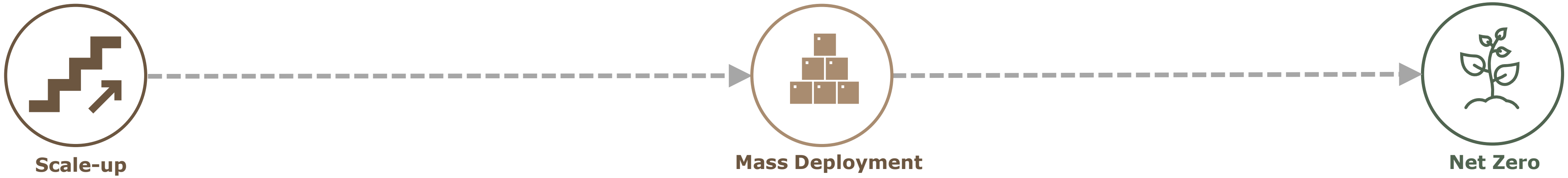
- Sharing of subsurface data between GCC and industry to identify prime stores
- Sharing of research and technologies between GCC and industry to avoid repetition
- Sharing of GCC transport and storage plans to develop an integrated plan that captures synergies across the GCC
- Global knowledge sharing on technologies and costs
- Further engagement with NOC's and industry to agree the framework for ownership of T&S assets

Review of progress both regional and global to check strategy fits with GCC and industry targets and refine where appropriate

Strategy Developed
Global Engagement
Industry Engagement
GCC Engagement

- Delivery of a unified GCC strategy of CCUS and hydrogen with synergies built in
- Review of costs for projects based on early deployment of FOAK globally and in the GCC
- Engagement with industry to ensure pipeline of projects fits into planned hub strategy
- Follow up with NOC's to ensure they are set to own and operate the T&S infrastructure and are aligned with strategy
- Regional GCC engagement to align deployment in country and identify any support needed from other GCC members

Beyond scale-up stakeholder engagement needs to verify progress regionally and globally and adjust the roadmap as appropriate to reach Net Zero



Global knowledge sharing from FOAK projects and reality check with updated NDC's

GCC Engagement

Industry Engagement

Targets

- Regional engagement with GCC to review updated NDC's in relation to the strategy
- Rolling program of engagements to resolve any bottlenecks in deployment and share knowledge
- Engagement with harder to abate industries to organize pilots that will connect to developing clusters and hubs
- Sense check of targets and KPI's against operational performance of early projects in the GCC and globally

Reality check with global net zero progress and updated NDC's, locking in of cost savings to achieve cheapest possible mass deployment

Global Engagement

Targets

GCC Engagement

Strategy Developed

- Engagement globally to learn from pilot projects and accelerate deployment
- Re-evaluation of targets in light of global progress towards net zero
- Review of costs for projects based on early deployment of NOAK globally and in the GCC
- GCC engagements to update strategy and develop strategy for NET's for those sectors that will be impossible to abate
- Unified GCC strategy for NET's

Tracking progress to net zero and consolidating learnings for NET's to go beyond net zero and begin carbon reduction phase

GCC Engagement

Global Engagement

Industry Engagement

- GCC engagement to adjust strategy and deployment to meet net zero 2060 targets
- Net zero pledge reality check based on global progress
- Review of costs for projects based on early deployment of FOAK globally and in the GCC
- Industry engagement with those sectors that will rely on NET's
- Engagements with owners of NET technology to identify bottlenecks

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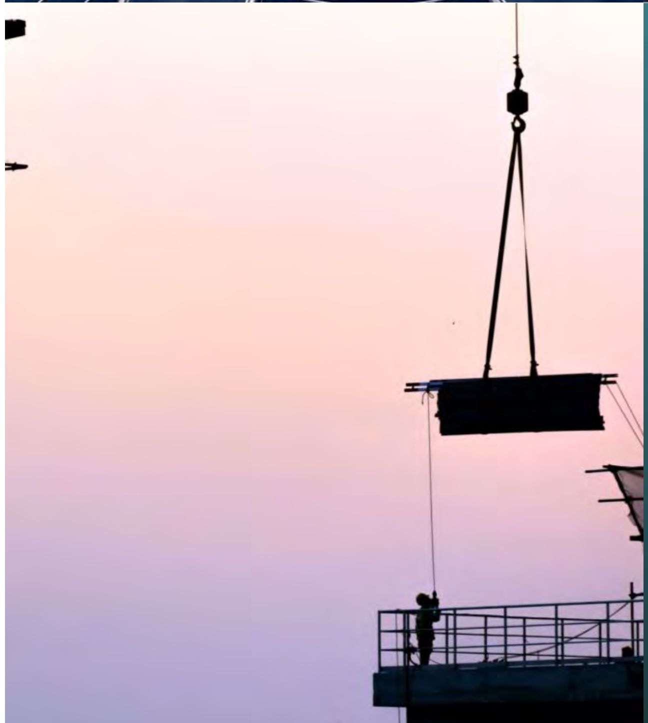

Policy and regulation will spur investment and give confidence to investors to deploy the capital necessary for development of projects

- Successful deployment of CCUS and hydrogen projects requires policies to be implemented that are comprehensive, sets credible long-term targets and is fully funded, so that projects can earn the rate of return required by investors. Without these steps in place it will be very difficult to attract developers of projects to the GCC and encourage local companies to invest in order to maintain the consistent and substantial deployment necessary to support decarbonization.
- Following from COP26, there is substantial international competition for hydrogen developments, notably between NW Europe, Australia, N Africa and the USA. In addition many other countries are looking at the opportunity. CCUS is going to be an important enabler of these plans particularly for states with significant natural gas endowments and will separately be required to meet domestic decarbonization agendas.
- This competition between sovereign states to attract developers, technology providers and manufacturing, means that the GCC will need to make its CCUS and hydrogen programme at least as attractive as that of other sovereign states, taking account of local advantages and challenges. Key aspects of this attractiveness will include:
  - Inventory of national carbon sinks (to spur development of clusters and hubs and benefit from economies of scale)
  - national renewable energy resource maps (to ‘sell’ the GCC’s renewable resources to international developers and equipment providers and enable green hydrogen);
  - clear, coherent and credible CCUS and hydrogen policy;
  - compensation commensurate with the resources, risks and uncertainties of operating in the GCC, with support levels taking account of the available resources but also uncertainties associated with early investment in CCUS and hydrogen in the GCC.
- What follows is a list of requirements for consideration when developing policy as well as an illustrative example of what potential policies need to be developed before outlining specific actions for policy that form the roadmap

There are key elements of CCUS and hydrogen policy that will need to be accounted for during the next 12 months to enable development

REQUIRED ELEMENTS

- Set firm targets for CCUS and hydrogen deployment
  - Developers and manufacturers need to be able to see a clear 'runway' for future developments, not just single projects or pilots.
  - Deployment targets set at intervals for 2025, 2030 and 2035 should be sufficient for this.
- Define eligible CCUS and hydrogen technologies and projects
  - Developers and manufacturers need to be sure that their technologies will be eligible for support both now and in the future, so clear guidance should be given on any eligibility restrictions.
  - It is not advisable to define targets by technology type or to try and specify any particular brand, type or size of technology, as developers prefer to make these choices based on their international experience.
  - These policies can also be used to shepherd industries into taking action early and support cluster and hub development.
- Set out remuneration mechanism
  - There is no single design for support arrangement that must be adopted. What is more important is that the mechanism is clearly understood, is robust to change and free from political interference.
  - Support levels to future projects should be capable of being changed under a transparent and principled process but retrospective changes to support to existing projects must be avoided to maintain investor confidence.
  - Potential scheme designs have been outlined in Chapter 6 - Business Models.
- Define ministerial, agency and regional responsibilities for facilitating CCUS and hydrogen deployment
  - It is important that supporting CCUS and hydrogen policies are co-ordinated and complementary.
- Define intended structure for CCUS and hydrogen sector
  - The policy should set out a vision for how Government intends the sector to develop, this provides a context for investors and allows visibility of any unintended consequences which may require intervention to address.

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These key elements combine to form a CCUS and hydrogen regulatory framework that will set up the sector for success during scale-up

REQUIRED ELEMENTS

- Co-ordinate policy on access, licensing and policy to remove structural constraints
  - Many of the barriers to the successful deployment of CCUS and hydrogen are nonfinancial, such as structural constraints involving consenting, land-use, network access or supply chain limitations and are often unintended. It is vital that the policy assesses and remedies these constraints.
- Describe how CCUS and hydrogen policies fits into larger energy market, export and industrial policy and might evolve with changes in wider markets
  - CCUS and hydrogen policies are just one of a wider range of energy and industrial policies that may include the liberalisation of electricity markets, fuel security, consumer pricing and job creation.
  - Policy across these areas will need to be co-ordinated and managed.
  - The policies will also need to fit with NDC pledges by GCC countries and to the wider COP commitments in the path to net zero

HIGH LEVEL REGULATORY FRAMEWORK

General law
- Competition
- Environmental

Sector specific law
- CCUS
- Hydrogen
- Other

Principal regulation
- CCUS and Hydrogen Target Model regulation

Licences
- Production
- Transport
- Storage
- Distribution
- Other

Standards, codes, certification, regulations
- **Competition**: Market rules, market power mitigation, monitoring,
- **Monopoly**: Price control, service, quality, incentives …
- **Technical / Operational**: Operating codes, metering, connections, balancing …
- **Standards**: Safety standards, equipment standards, …
- **Hydrogen product certification**: Blue, green, pink hydrogen
- **CO_2 Stream purity**
- **Carbon Capture as a Service (CCaaS)**

Policy and regulatory frameworks for CCUS and hydrogen should be the focus of the next 12 months with all in place for 2023

Phase 1

CCUS and Hydrogen strategy

- Review existing work on CCUS and H2 in GCC
- Review international examples of CCUS and H2 strategies
- Inventory of CO_2 emitters and opportunity for abatement or substitution
- Establish likely sources of supply and demand for H2
- Establish likely spatial distribution of supply/demand and transport needs
- Establish likely temporal distribution of supply/demand and storage needs
- Develop overarching philosophy, design principles and strategy

Target models

- Review target models in other jurisdictions
- Identify key investment/operational decisions
- Develop target model
- Review existing law/regulation

Detailed Roadmap

- Review roadmaps in other jurisdictions
- Develop physical evolution of the system over time
- Develop policy/regulatory evolution over time
- Map dependencies
- Hydrogen monitoring plan

Phase 2

Policy and regulatory framework

- Develop the list of new policies/laws/regulations/standards etc. ("regulations") etc needed to enable the Target Model
- Develop main provisions of the policies/laws/regulations/standards
- Draft text for new 'principal' CCUS and H2 regulation and any changes to existing laws/regs

Access to electricity for hydrogen production

- Electricity market/system fundamentals, policy and regulation
- Investment/operational decisions and responsible entities
- Obligations, incentives and pricing
- Electricity provenance certification
- Future policy and regulation

Phase 3

Certification

- Review certification schemes in other jurisdictions
- Select certificate types to develop
- Develop certificate requirements
- Develop implementation roadmap
- Draft regulation

Standards

- Map landscape of potential standards
- Identify source of standards
- Allocate responsibilities for new standards
- Draft the standards

Licensing

- Review licensing practices in other jurisdictions
- Review existing licensing framework in GCC
- Develop longer-term CCUS & H2 licencing process
- Licensing implementation roadmap

Policy actions are required at each stage of the roadmap and need to encourage further development until scale up is reached

Building the initial framework for policy and regulation and development of first business models

Policy · Standards · Support · Industrial Strategy

- Policy review to ensure there are no barriers for large scale deployment of CCUS and production and use of hydrogen
- Standards for CO_2 and hydrogen for internal consistency and possible alignment with international standards
- Development of a business model based on international best practices and provides necessary support for development
- Updated industrial strategy to account for development of low carbon industry and identify opportunities for new industry growth

Supporting initial development and learning while doing, development of low carbon industrial strategy

Policy · Contracts · Industrial Strategy

- Promotion of CCUS and clear subsidy and funding models for both CCUS and hydrogen
- Initial contracts for H_2 and CO_2 domestically
- Initial export contracts for hydrogen
- Development of policies for use of hydrogen in industry and timelines for compliance
- Framework for low carbon products industry
- Development of new industries that utilize CO_2 and associated strategy for roll out

Adjustment of business model and support to meet policy aims, legal targets to facilitate development and growth

Support · Legal · Industrial Strategy · Contracts

- Tweaks to business model, subsidies and support based on initial development
- Reality check on cost reduction to ensure support mechanisms reflect learning curve
- Legal targets and framework to drive policy and provide certainty
- Low carbon manufacturing industrial policies and updated industrial strategy reflecting progress
- Long-term contracts for export of H_2 and/or derivatives at scale

At scale-up the framework is in place for industry to take the lead, but further policy and economic tweaks will be needed to reach Net Zero

Scale-up → **Mass Deployment** → **Net Zero**

Scale-up

Expansion of low carbon manufacturing support and new industry tied to CCUS and hydrogen

Policy, Support, Legal, Contracts

- Update NDC's and design a business model for large scale development with a taper for subsidy phase out
- Economic reforms and carbon pricing model consistent across GCC or aligned with emerging global model
- Legal obligation for easy to abate sectors to be fully decarbonized, timeline for remaining industries to decarbonize
- Initial contracts for low carbon goods

Mass Deployment

Support for NET and expansion of low carbon goods and hydrogen exports, phase out subsidy support, roll out of CCaaS

Policy, Support, Industrial Strategy, Contracts

- Internal GCC carbon market tied into global market
- Review of business model as hubs and clusters grow and for hard to abate sectors
- Business model for NET providers (price for removals)
- Development of CCaaS for countries that lack storage capacity
- International investment in CCUS and hydrogen projects deploying expertise
- Initial contracts for CCaaS

Net Zero

Removal of support from mature market, legal frameworks for remaining unabated sectors and expansion of NET and CCaaS

Policy, Contracts

- Policy tweaks to ensure sustainable mature industries
- Long term contracts for CCaaS
- Contracts for abatement via NET for global emitters in impossible to abate sectors

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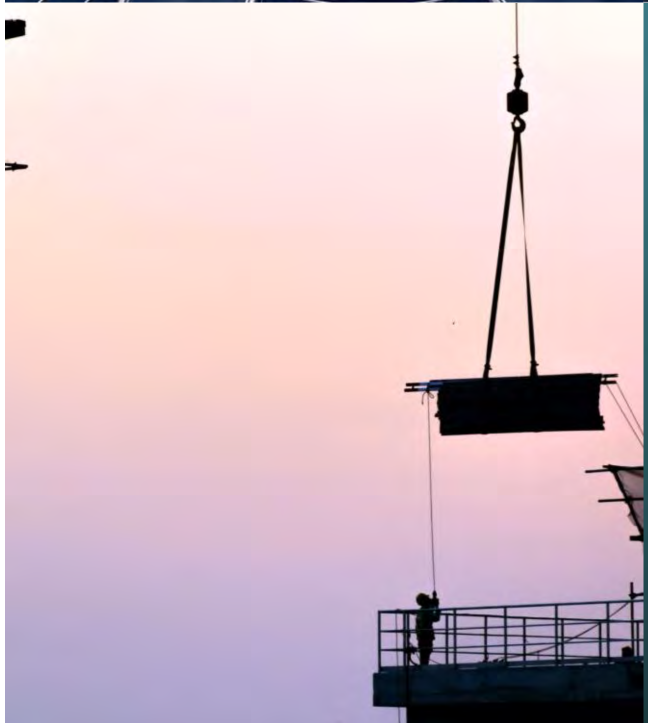


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Although R&D and pilots are already advanced in the GCC additional work will need to be done to inform policy and strategy

- To capture the true value of CCUS and hydrogen, the GCC must capture and create the intellectual capital associated with low carbon technologies as well as inform policy and strategy choices
- Much work has already been done on pilot plants (particularly in Saudi Arabia, Qatar and UAE) but promising low carbon technologies such as pyrolysis and oil to hydrogen need to be fully investigated and piloted in the GCC before any consideration of commercial deployment
- The adaptation of existing technologies to the GCC environment may create opportunities for evolved technologies to be deployed not only in the GCC but exported more widely. Certainly research into better solvents and processes for capture is an enormous area of research with lots of opportunity for the GCC. This work could take a number of shapes:
  - Establishing research clusters within co-located research parks
  - Developing and making available test facilities (e.g. dust and temperature testing) for a range of technologies.
  - Commissioning and funding applied research projects and demonstration projects.
  - Sponsoring and supporting the development for demonstrating projects through to commercialization in the GCC and abroad.
  - Co-ordinating applied research and knowledge transfer between technologies, companies and academia.
  - Commissioning training courses and vocational degree courses from GCC universities to provide the necessary skill base for the emerging CCUS and hydrogen industry.
  - Establishing an international exchange programme for seconding staff, lecturers and students between GCC companies and international developers and technology owners and/or appropriate vocational courses at global partner universities.
- What follows is a list of requirements for consideration when developing a R&D framework and the requirements that feed in to both stakeholder engagement and policy, this is reinforced by a listing of specific actions for research and development that form the roadmap

In addition to policy, 2022-2023 should be used to build strategy and likely demand for CCUS and hydrogen as well as subsurface understanding

REQUIRED ELEMENTS

- Adaption of existing technology to the GCC environment and resolving emerging issues, alongside a longer-term research programme to encourage the development of emerging CCUS and hydrogen technologies and bring them to demonstration phase
- We envisage this programme to include:
  - designing, commissioning and funding research programmes at GCC universities, and potentially internationally;
  - co-ordinating research between GCC academic institutions; and
  - establishing an international centre of excellence in the GCC for new energy, CCUS and hydrogen technology research with annual international symposiums encouraging academics and professionals around the world to participate.
- Carry out market assessments for hydrogen and low carbon products to scale deployment
  - Development will need to be scaled between domestic decarbonization efforts and opportunities for export of hydrogen and low carbon products to meet demand

SUBSURFACE REQUIRED ELEMENTS

- Delineate individual saline aquifer stores
  - This study has highlighted the most promising areas but for development of hubs it will be necessary to delineate and quantify individual carbon stores
  - A full catalogue of stores for each country is expected to take 12-18 months depending on available data
  - If no data exists it may be necessary to collect it which may extend the study period from between 18-36 months
  - Exploratory drilling and coring of the most promising stores in preparation for cluster and hub development will be required
- Full inventory of depleted oil and gads reservoirs and associated volumes available for storage
  - This data likely already exists and will need to be reviewed which is expected to take between 3-6 months
- Research and quantification of opportunities in the Oman ophiolite

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Although much research and piloting has been done ahead of initiation there are still important questions to answer to ensure a robust strategy

Initiation → **First Of A Kind** → **Early domestic growth** → **Scale-up**

Initiation

Baseline studies to design infrastructure, definition of opportunities and technologies that can be deployed

Studies · Market Reports · Pilot Projects · R&D

- Identification of delineated CO_2 stores and associated volumes.
- Full catalogue of industrial emissions and substitution or abatement opportunity.
- Markets analysis for hydrogen, low carbon products and CCaaS and global demand for CO_2 storage
- Early pilot projects should be supported in as diverse a range of opportunities as possible
- R&D to investigate oil to H_2 options, NET's, CO_2 utilisation options, CO_2 and hydrogen transport, H_2 production

First Of A Kind

Improving existing capture tech and testing emerging capture tech to develop clusters

Market Reports · Pilot Projects · R&D

- Studies on global demand for low carbon products (steel, ammonia, methanol)
- Pilot project for advanced cement emissions capture
- Pilot project for advanced steel emissions capture
- R&D to improve capture tech for petrochemicals, fertilisers/ammonia, methanol, gas processing

Early domestic growth

Expansion of capture industry sectors and pilots for pyrolysis and oil to H_2

Pilot Projects · R&D

- Pilot project for large scale pyrolysis
- Identification of sites for oil to hydrogen pilot
- Integration of learnings from pilots in cement and steel into development of new plants
- R&D to improve capture tech for cement, refining, steel, power, industrial heat, LNG, aluminium

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The outcomes from research during the 2030's will shape the detail at scale-up towards demonstration and deployment of further pilot projects

Scale-up → Mass Deployment → Net Zero

Scale-up

Roll out of pyrolysis and oil to H_2, Expansion of low carbon industry and capture sectors to build out existing and new hubs

Market Reports

Pilot Projects

R&D

- Markets analysis for carbon black and derivatives to right size pyrolysis roll out
- CCaaS market assessment
- Oil to H_2 pilot
- Pilot of NET (DACCS) projects as well as expansion of low carbon manufacturing
- CO_2 shipping and infrastructure research
- Large scale H_2 and derivatives shipping research
- R&D to investigate advances in capture and utilisation

Mass Deployment

Pilot of CCaaS and research into removals technologies to enable carbon negative future, improvement to existing capture tech

Market Reports

Pilot Projects

R&D

- Markets analysis for carbon removals and NET and associated derivative products such as zero carbon fuels
- CCaaS pilot
- R&D for removals tech and emerging technologies that would help impossible to abate sectors emissions

Net Zero

Full switchover to hydrogen, electric or CCUS for all industry and transport. Research focus on improved technology and DACCS

R&D

- R&D to improve capture tech and identify new uses
- Incremental improvements in technology for hydrogen, infrastructure
- Continuing research into carbon removals technologies

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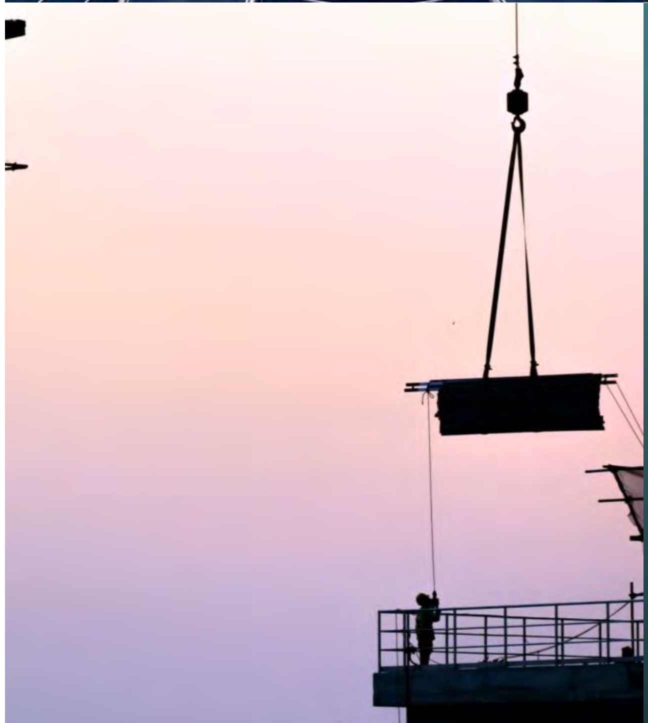
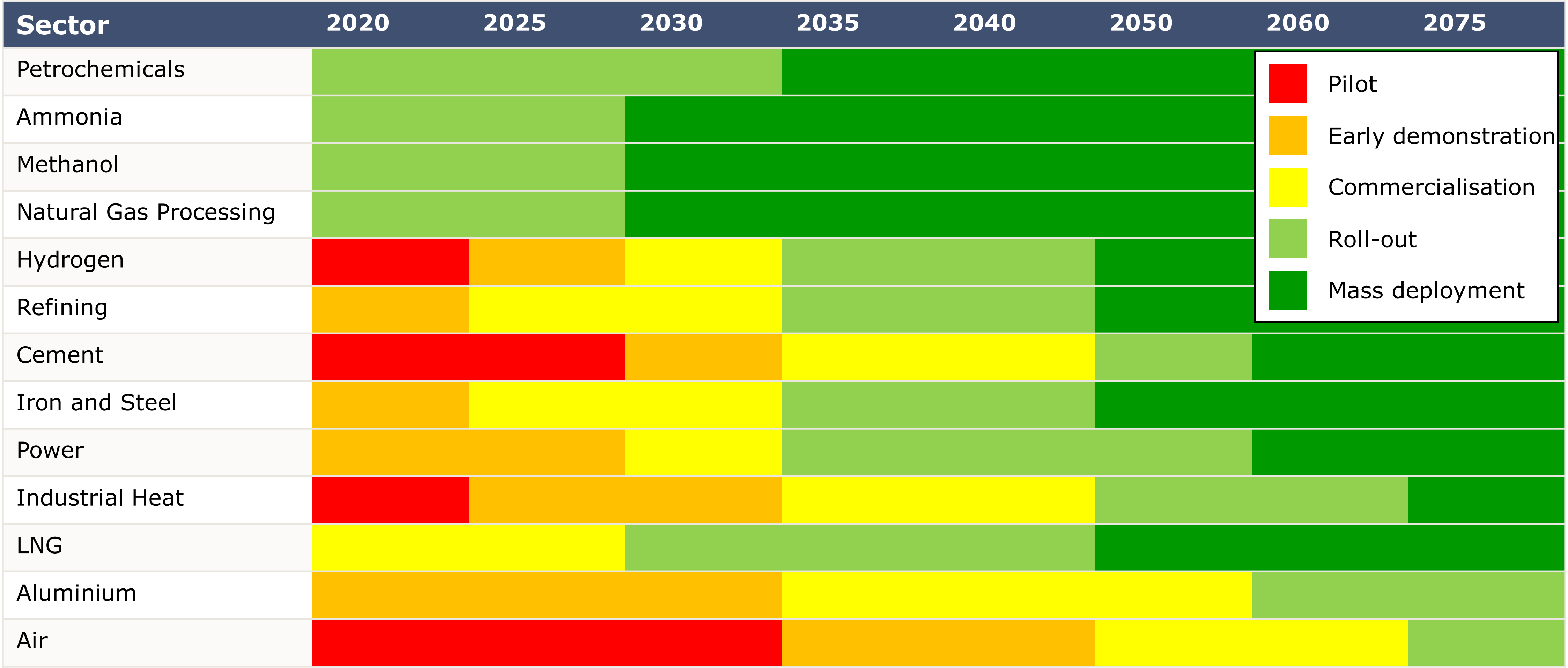



Development of CCUS and hydrogen in the GCC will likely occur in phases as technology advances and infrastructure is built out

- In addition to CCUS and hydrogen projects it will be necessary to accelerate the deployment of renewables. Whilst this is outside the scope of this study the impact of that roll out has significant implications for this roadmap.
- Green hydrogen will require massive expansion of renewables, whilst power requirements will also dictate how many existing power plants are likely to need retrofitting. The GCC has huge potential for solar meeting a large amount of energy demand which could also provide solutions for aluminium production, industrial heat and desalination.
- As such an understanding of the roll out of renewables will need to be carried out and aligned with the CCUS and hydrogen deployment strategy.
- From 2010-2020 across much of the GCC initial research and pilot projects were carried out such that deployment of commercial scale plants can now begin. Although expertise exists in the GCC from these pilot projects it is recommended to recruit international development companies to locate in the GCC to ensure a pipeline of resources for what will be a very challenging scale up. These companies should have proven abilities to deliver projects in the region, develop projects in technologies appropriate to the GCC, create local development teams and transfer knowledge to create employment opportunities and raise capital, construct and operate large scale projects and sizeable development 'pipelines'.
- It is envisaged that the scale-up and mass deployment of CCUS and hydrogen in the GCC will follow a three phase approach. Initial focus will be on development and deployment of a single CCUS hub at Jubail, Saudi Arabia, to establish a sufficiently sizeable project pipeline (in terms of clusters) to justify investment in transport and storage infrastructure. The second phase will be the addition of two additional hubs and associated clusters (most likely two from Abu Dhabi, Oman, Qatar and Yanbu, Saudi Arabia) depending on storage options. The third phase is the mass deployment of clusters to tie into these three hubs and the development of an undefined number of additional hubs where they make sense.
- A key decision in this deployment will be the extent of sharing infrastructure across borders (whether hubs, pipelines, clusters, storage, import/export, etc.) which will tie back to the strategy development and GCC engagements

Ease of abatement varies across industrial sectors and it will be necessary to pilot some projects before they are connected to clusters and hubs



The GCC should target development of 3 hubs by 2035 based around easy to abate industrial sectors, but pilot tougher sectors early

PHASING OF HUBS

- We would recommend the first hub be developed at Jubail, Saudi Arabia, given the diversity of industries available to connect in clusters and the size of the emissions within 50km of the hub – however this is contingent on sufficient storage being available
- For geographic and industrial diversity (provided storage is available) we would recommend Abu Dhabi and Oman being the second and third hubs
- This spread of hubs should maximise the amount of clusters that can feed in for the easy to abate sectors and allow the building out of an infrastructure backbone for both CCUS and hydrogen
- Additional hubs can be developed once suitable storage is identified and provided sufficient emissions from clusters is available
- In the roadmap each hub is expected to experience growth until it has reached its storage capacity which we have arbitrarily set at 20 years based on existing global projects, after which the site would move into long term monitoring – however this could be longer depending on the storage size, injection rate and design

PHASING OF CLUSTERS

- As shown previously the maturity of capture related to industry varies with purity of CO_2 stream and the process
- As such we would expect high purity, high density, easy to capture streams being the first industries to develop in a cluster. At present this would be ordered natural gas processing (including hydrogen), fertilisers/ammonia, methanol, steel, power, refining, cement, LNG, industrial heat, Aluminium, direct removal (air)
- Initial clusters would therefore be developed around gas processing, ammonia, methanol and petrochemicals
- Given the large emissions associated with power, cement, steel, desalination and refining we would expect early pilots for these industries to accelerate their tie-in to the clusters and ultimately hubs
- Some of these sectors have alternatives to CCUS for emissions reduction
- What follows are specific actions for infrastructure development that form the roadmap

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The focus now should be on deployment of proven technologies and picking the ‘low hanging fruit’ establishing a pipeline of projects and progress

GCC yet to develop sizeable domestic CCUS industry or low carbon hydrogen production

Scoping

- Identification of first clusters based around gas processing, ammonia, methanol and petrochemicals
- Early pilot projects should be supported in as diverse a range of industries as possible
- Identification of sites for high impact pilots (power, cement, steel)

Design

- Pre-FEED and FEED for Hub 1 at Jubail

Infrastructure

- Feasibility studies for carbon transport backbone and cross border connections

First hubs, infrastructure and carbon storage across the GCC. Planning for hydrogen and low carbon products

Project Execution

- Development of first cluster projects
- First CCUS hub operational focusing on mature capture technology decarbonizing gas processing, ammonia and petrochemicals

Design

- Pre-FEED and FEED for high impact pilots (power, cement, steel)

Infrastructure

- First components of CCUS infrastructure backbone
- Feasibility studies for large scale hydrogen and derivatives exports and storage

Early domestic growth aligning projects to developing hub and clusters

Scoping

- Identification of sites for third generation clusters (refining, LNG, industrial heat, desalination)
- Development of high impact pilots (power, cement, steel)

Project Execution

- Additional cluster development for petrochemicals, ammonia, methanol and gas processing (including hydrogen)
- Start development on hubs 2 & 3
- Expansion of existing hub to include new capture streams

Decarbonisation

- Large scale decarbonisation of gas processing, ammonia, methanol

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With the backbone infrastructure in place the goal is to rapidly scale-up and deploy towards a regional corridor that caters for all industries

Scale-up

Development and expansion of three hubs and scale up of hydrogen production and exports. Focus on low carbon manufacturing

Infrastructure
Project Execution
Scoping
Decarbonisation

- Connection of additional hubs to carbon backbone and investigate cross border infrastructure
- Development and expansion of 3 hubs which cover full suite of industrial sectors
- Additional cluster development for power, cement, steel
- Expansion of existing hubs to include new capture streams
- Identification of sites for hard to abate sectors) & development of additional pilots (refining, LNG, industrial heat, desalination)
- Large scale decarbonisation of petrochemicals, hydrogen

Mass Deployment

CCUS Industrial corridor across the GCC with cross border transport and storage. Expansion of NET's and switchover to hydrogen

Infrastructure
Project Execution
Decarbonisation

- Expansion of hubs and clusters into CCUS corridor across the GCC including cross border transport and storage
- Expansion of existing hubs to include capture streams from all sectors
- Expansion of NET's to decarbonize O&G production and impossible to abate sectors
- Expansion of low carbon goods, carbon black and derivatives
- Large scale decarbonisation of cement, refining, steel, power, LNG, desalination

Net Zero

Full switchover to hydrogen, electric or CCUS for all industry and transport. Expansion of DACCS for all other sources

Infrastructure
Project Execution
Decarbonisation

- Integrated regional infrastructure for CCUS
- Expansion of hubs and clusters as appropriate to meet industrial strategy and ensure zero emissions
- All industry decarbonized via CCUS or DACCS
- Negative emissions O&G production for niche needs (pharmaceuticals, plastics, etc.)

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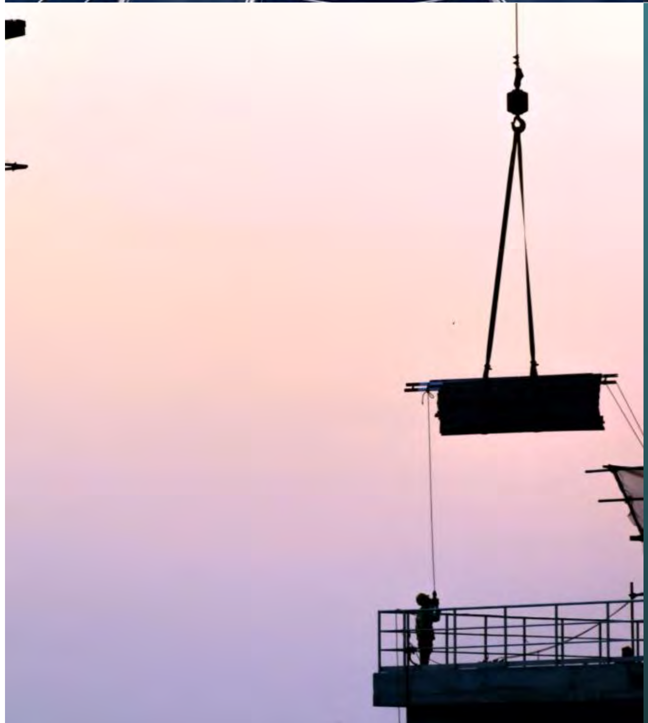

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CCUS alone will not decarbonize the globe and hydrogen in the GCC is a good opportunity to seize both for domestic uses and export

- As reducing GHG becomes more important across the globe, the demand for low carbon fuels and products will grow exponentially as the need for oil and gas declines. The GCC states can play a major role in supplying global low carbon needs.
- As shown earlier the GCC is well placed to take advantage of hydrogen to assist with domestic decarbonisation and provide a new export stream, though it is still unclear whether this will be through hydrogen itself or hydrogen derivatives such as ammonia or methanol
- The GCC has already carried out pilots for blue ammonia and other blue and green hydrogen projects are currently in development, but like CCUS a strong policy and support framework needs to be in place before it can be deployed at scale
- Hydrogen stakeholder engagement, policy and research has already been addressed in those sections of the roadmap and what follows here is specific infrastructure relating to hydrogen that will need to be developed in addition to the CCUS infrastructure
- There is no single hydrogen pathway and set of end-users, much is still to be defined, but many options and pathways are open to each of the GCC states. The race is already underway to decarbonise the power sector, fuel and industrial production across the globe and the opportunity to develop low carbon industries based on a hydrogen feedstock should be seized.
- In the path to 2030 the focus needs to be on deployment of FOAK large scale plants to compliment the smaller pilot projects and demonstration projects already in development in the GCC
- The target will be to scale up and bring costs down such that in the period 2035-2045 all domestic grey, black and brown hydrogen is replaced with low carbon (blue and green) hydrogen
- It is envisaged that early exports will utilise existing infrastructure and will be in hydrogen derivatives such as ammonia
- What follows are specific actions for hydrogen production that form the roadmap

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Action on hydrogen is required early to deploy the first of a kind plants and begin the decarbonization of existing production as well as ready exports

GCC yet to develop sizeable low carbon (blue) or renewable (green) hydrogen production with all production currently carbon intensive (grey)

Scoping

- Identification of additional locations for blue hydrogen plants in industrial clusters
- Identification of locations close to demand centres for green hydrogen plants

Design

- Early pilot projects should be supported in both production and hydrogen derivatives (blue and green ammonia, methanol and steel)
- Pre-FEED and FEED for FOAK blue hydrogen plant co-located with the Jubail CCUS clusters

Infrastructure

- Feasibility studies for hydrogen transport backbone and cross border connections

Construction of FOAK blue hydrogen plant, planning for green hydrogen and low carbon products developments

Design

- Pre-FEED and FEED for first large scale green hydrogen plants
- Pre-FEED and FEED for low carbon ammonia, methanol and steel projects

Project Execution

- Planning and DE for first large scale blue hydrogen plants

FOAK blue hydrogen plant online and exports of blue ammonia and methanol begin as hydrogen specific infrastructure still in development

Project Execution

- Completion of FOAK blue hydrogen plant and start of production
- Planning, DE and Construction of first large scale green hydrogen plants dedicated to export
- Planning, DE and Construction of low carbon ammonia, methanol and steel projects
- Construction of smaller scale green hydrogen plants for offtakers

Exports

- Export of low carbon derivatives (ammonia, methanol)

Infrastructure

- Pre-FEED and FEED for hydrogen transport backbone

At scale-up the global market is established and deployment should take this into account, whilst catering for domestic demand and new uses

Scale-up → **Mass Deployment** → **Net Zero**

Scale-up

Scale up of up of hydrogen production and exports, planning and development of oil to H_2 and pyrolysis, low carbon products

Infrastructure, Design, Project Execution, Exports, Decarbonisation

- Construction of the hydrogen backbone and investigate cross border infrastructure
- Pre-FEED and FEED for FOAK large scale pyrolysis and oil to H2 projects
- Additional blue and green hydrogen developments and expansion of low carbon products
- Ramp up of exports to meet new global hydrogen market demands
- Significant reduction of grey, black and brown domestic hydrogen production

Mass Deployment

Global hydrogen market matures and more industry switches over to hydrogen as global oil and gas production declines

Infrastructure, Project Execution, Decarbonisation

- Expansion of hydrogen use for seasonal storage
- Expansion of blue and green hydrogen into regional hydrogen hub including cross border transport and storage
- Completion of FOAK pyrolysis and oil to H_2 plants and start of production
- Switchover to hydrogen for appropriate industries and end users such as industrial heat, shipping and aviation
- Elimination of all grey, black and brown domestic hydrogen production

Net Zero

Full industry switchover to hydrogen, switchover from blue to green hydrogen as costs fall, mature export market for hydrogen

Project Execution, Decarbonisation

- Market led production of hydrogen for domestic use and export
- Expansion of pyrolysis to meet global carbon black and derivatives demand
- All industry that can switch to hydrogen has done so, other industry and emissions decarbonized via CCUS or DACCS
- Significant reduction of blue hydrogen production as plants reach end of life and green hydrogen is cheaper and more flexible

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CHAPTER 11

Conclusions

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CCUS has promising applications across multiple industrial activities in the GCC and will play a role in the decarbonisation of hard-to-abate industries

Area	Conclusion
Country-level emissions	– Saudi Arabia and the UAE account for more than 60% of GCC CO_2 emissions driven by the high activity of their oil refineries, petrochemical plants, and power sectors – Bahrain has the lowest CO_2 emissions in the GCC region due to its small population and relatively low economic activity with aluminium smelting being the prime source of these emissions – Qatar is expected to join Saudi Arabia and the UAE as a high CO_2 emitter as it expands LNG, petrochemicals and aluminium production
Industry-level emissions	– Electricity generation continues to be the industry with the highest CO_2 emissions in the GCC because the majority of state-owned plants and independent power producers use oil and natural gas as feedstock. – The petrochemicals, oil refining, and aluminium sectors are the main CO_2 emitters after power generation – Despite reductions in emission intensities across the various industries, CO_2 emissions continue to increase due to the expansion of production capacity
CCUS in industrial applications	– CCUS is technically and economically more suitable for industries characterised by high purity CO_2 streams which result from the ease of separation of CO_2 from other gases and impurities in flue streams. These industries include petrochemicals, fertilisers, methanol, and to a lesser extent aluminium, steel and oil refining – Despite being the main contributor to CO_2 emissions, the application of CCUS in the power sector will be limited to new build rather than retrofitting existing plants due to technical and contractual obstructions

The GCC can be a world class hub for CCUS, with significant potential in both depleted reservoirs and saline aquifers close to emissions clusters

Area	Conclusion
Presence	– Significant opportunity across 11 sedimentary sequences and the Oman ophiolite – Storage density is highest in the Rub’al Khali basin and Kuwait
Quality	– Risks are optimal in well-sealed sandstones and shallow carbonates with proven reservoir trends – Poorest risks are in deep, tight carbonates – injectivity and uncertain reservoir distribution – Oman ophiolite offers uncertain efficiency but large potential volumes
Volumes	– Total best case storage volume 127.5Gt of CO_2 – GCC is technically competitive with other regions with respect to storage presence, quality and volumes

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The GCC region has the potential to develop active CCUS hubs due to the availability of natural sinks and concentrated CO_2 emissions

Area	Conclusion
High purity CO_2 emissions	– The GCC region is home to several industries that emit high purity CO_2 streams which could be captured at low costs and without technical complexities ideal for carbon capture applications – Industries that emit the highest purity streams include petrochemicals, fertilisers, methanol, natural gas processing, and hydrogen production at oil refineries, steel facilities, and GTL plants – Although the power and aluminium sectors produce dilute CO_2 streams, they must not be overlooked as they are the main CO_2 emitters in the GCC region, and might require retrofits to meet carbon targets
Natural sinks	– The GCC region is endowed with natural geological sinks that can store CO_2 for hundreds of years to come with the Rub’al-Khali saline aquifers being most notable ones giving Saudi Arabia a competitive advantage in terms of CO_2 storage capacities – Saline aquifers and the Oman Ophiolite are sufficient to serve CCUS developments in the GCC region – On the very long term, depleted gas reservoirs will add to the GCC’s CO_2 storage capacities
Promising hubs	– Jubail, Northern Qatar, and Abu Dhabi seem to be the most favourable CCUS hubs in the GCC due to the high share of high purity CO_2 emissions and their proximity to the Rub’al-Khali Basin. – The Governorate of Muscat in Oman has a variety of CO_2 emitting industries including high purity streams and has direct access to the Oman Ophiolite – Bahrain and Kuwait have lower emissions than other GCC member states and their emissions could be clustered to make them active participants in the CCUS market

The GCC could realise significant economic benefits from decarbonisation as well as creating thousands of new jobs and protecting existing ones

Area	Conclusion
Macroeconomic Context	– Under various scenarios for decarbonisation, emissions across the Middle East will need to fall by between 56% and 90% by 2050 – The application of CCUS and/or the use of low-carbon hydrogen in production processes is needed to protect the jobs and output in key industrial sectors of the GCC – The expectation is that decarbonisation of key industrial sectors will ramp up slowly until 2030
New Market Opportunities	– The development of CCUS and Hydrogen will open up new market opportunities and protect income and employment in key industrial sectors – It is estimated that new market opportunities in hydrogen export and CCUS could add $15-44bn in gross value added (GVA) to the GCC in 2050 and support between 87k-245k jobs – the GCC is well placed to establish itself as a key producer and exporter of low-carbon hydrogen with a global market share of between 16% and 19% by 2050
Existing Industries and Investment	– Domestic CCUS deployment would see around $180bn of investment in CCUS infrastructure by 2050, supporting around 30k jobs in manufacturing, construction, operation and maintenance – Effective decarbonisation of industrial activity also enables the GCC to maximise its future oil and gas production and repurpose existing uses of oil and gas for export – By investing in CCUS and hydrogen, the GCC will protect employment and income in those sectors most affected by global decarbonization and meet its climate commitments

Since the GCC lacks a strong domestic driver for CCUS, a strong business model and incentive scheme will need to be deployed

Area	Conclusion
Existing business models	– A range of business models for CCUS have been developed around the world and can be summarised as either subsidy, revenue support, grants, loans, direct investment or mixtures of these – Without government subsidy CCUS projects generally only work where there is a revenue stream from EOR
Structure of business model	– Successful CCUS business models decouple value chain risk with separate models for capture, transport, storage and utilization – There needs to be an agreed carbon price, incentivization or penalty system in order to encourage CCUS deployment
GCC busines model	– IPP has been used successfully in the GCC for electricity and is a good framework to use for CCUS with a single buyer that fits with the natural monopolies many of the NOC's enjoy – Direct payments linked to volume captured and risk sharing to decouple cross chain risk needs to be the foundation of any model that is adopted – Early engagement and negotiations across the GCC are needed to develop a business model that handles imports and cross border transport

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CCUS costs can be expected to decrease by up to 43% in the GCC with a lower cost base compared to other regions

Area	Conclusion
Global cost reductions	– Capture technology cost reduction is expected to be global in nature based on 'learning by doing', economies of scale and reduced contingencies – GCC should encourage global roll out of CCUS to benefit sooner – Additional saving can be captured from falling financing costs associated with a lower risk premium as the perception of policy and technical risk reduces – The GCC should support ongoing R&D, particularly with next generation technology and hard to abate sector capture tech, since this will bring cost savings forward and allow more efficient hubs to be developed
Local cost reductions	– Transport and storage cost reduction is expected to be local in nature based on inherent competitive advantage from project execution, geology, land and labour costs – Distance, volumes, option, storage site location and business model will be the biggest levers in realizing cost reduction – Economies of scale and nature of storage alongside risk perception will drive cost reduction in the GCC
GCC specific advantages	– There are good reasons to expect that CCUS will be relatively low cost in the GCC based on low land costs, low labour costs, stable investment environment and history of successful CCUS projects – There are expected to be some barriers to rapid roll out of low cost CCUS largely due to the lack of an existing policy framework which should be a priority for GCC states to develop

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The GCC has significant potential to become a global leader in low carbon hydrogen production and export of low carbon goods

Area	Conclusion
Production	– In the long term green hydrogen production offers the best route for the GCC, but in the short term a twin track approach with blue and green hydrogen is recommended – Pyrolysis and the subsequent product carbon black could launch whole new industries in the region as well as satisfy current demand – Opportunity is not spread evenly and individual state hydrogen road maps need to be pragmatic and encourage collaboration rather than competition
Transport & Storage	– Ammonia currently offers the best at scale transport option based on cost and versatility – Salt formations in the GCC are an attractive option for long term storage for both balancing and export – Lack of pipeline routes to key market will require expansion and adaption of shipping and target of closer regional markets to cement competitive position
Exports	– Current regional demand and projected global demand supports the establishment of a hydrogen industry – Large market for hydrogen and low carbon derivatives such as ammonia and steel – Competition from other countries means that risks will need to be taken to secure market share, but exports will not compensate for lost oil revenues

The GCC has good conditions for large scale deployment of DACCS in the long term, with BECCS meeting the short-term need

Area	Conclusion
Need for carbon removals	– Carbon capture and storage alone will not be sufficient to decarbonise the economies of the GCC and carbon removal technologies will be required – Beyond their use in impossible to abate sectors carbon removal technology will be required to stabilise global temperatures and address historic emissions by removing them from the atmosphere
Carbon removal technologies	– Nine NET's are available but only BECCS and DACCS are credible solutions for the GCC to remove carbon – BECCS is cheaper in the short term but the ability for cost reduction is unknown and there are concerns over the sustainability of the process – DACCS is currently in early commercialisation but could prove cost effective in the GCC if the requirements for water are met and have the benefit of using less resources and having lower costs
Trends in carbon removals and voluntary offsets	– DACCS can be used to manufacture zero carbon syn-fuels which are one potential solution to replacing aviation fuel given the complications of using electric or hydrogen solutions – The voluntary offset market pays a premium for the removal of carbon, but these technologies are still immature and reforestation is currently the only credible large scale offset solution

The GCC needs to decide the pace of decarbonisation but there is a clear roadmap to 2030 that will need to be followed to set up for success

Area	Conclusion
Roadmap Development	– A roadmap has been developed to match the GCC net zero ambition based on 5 main phases: initiation, scale-up, mass deployment, consolidation and net zero – In the early 2020's the focus will be on gathering evidence and developing the policy, fiscal and regulatory framework as well as development of the first projects and collaboration to take advantage of synergies – From 2030 onwards the focus should be on scaling up to commerciality building on successful pilots and matching market demand with development
Pace of Opportunity	– There is still uncertainty in the pace of decarbonisation, demand for hydrogen and demand erosion for existing oil and gas production and 'high carbon' industrial products – The roadmap is flexible to adapt to changing reality and there should be reflection at a number of points to measure progress against both internal goals and global targets – The focus should be on getting the path to 2030 right to set the decarbonisation agenda in the GCC on the right course
Net Zero	– CCUS and hydrogen alone will not get to net zero and for the remaining emissions fiscal and policy support for carbon removals will need to be developed, but this is not expected to be needed until the latter part of the roadmap (2040-2060) – The GCC must choose early whether it wants to lead the CCUS and hydrogen agenda or respond to other states actions, choosing a slower path will likely lead to a lower market share for export products in low carbon and hydrogen

ANNEX 1:

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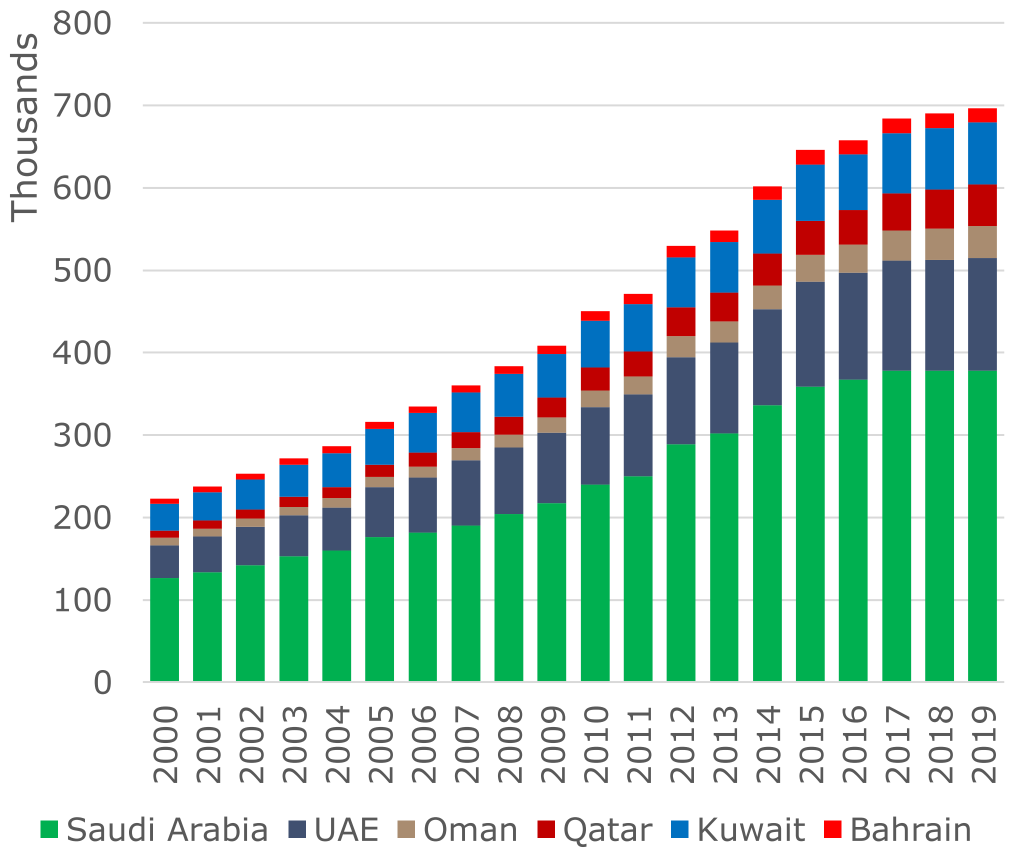
ANNEX 2:

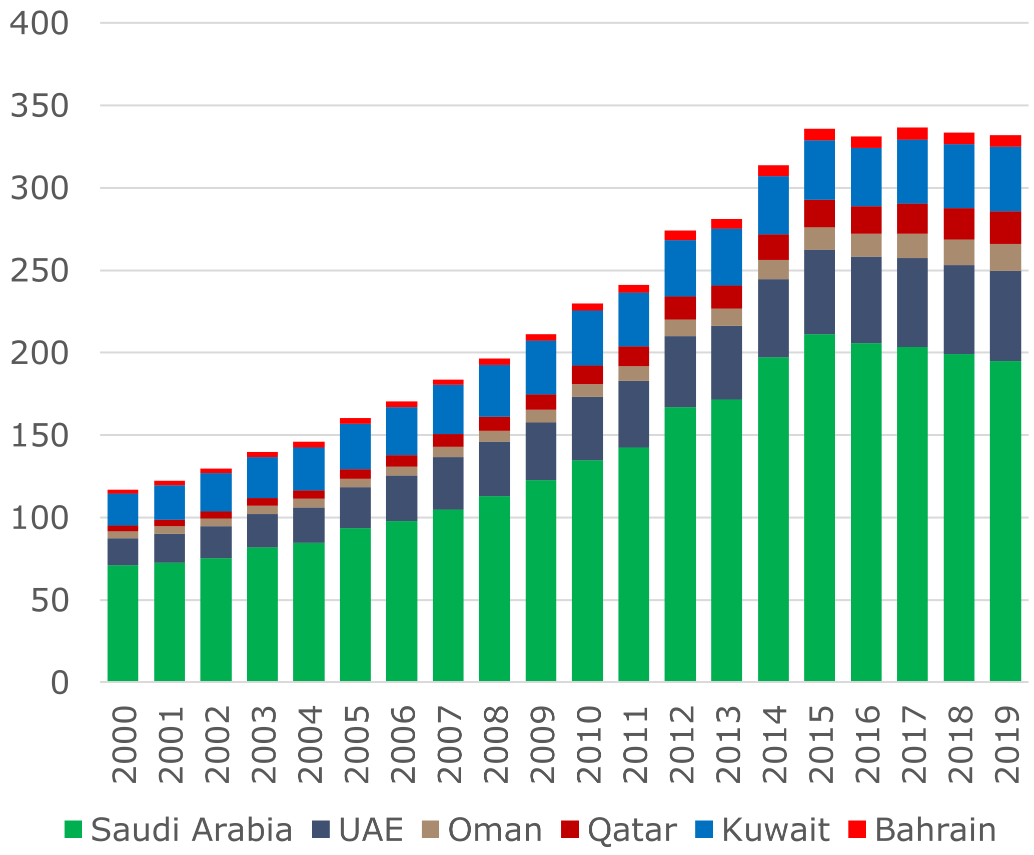
Technical Annex

Historical electricity production

ELECTRICITY PRODUCTION (GWH)

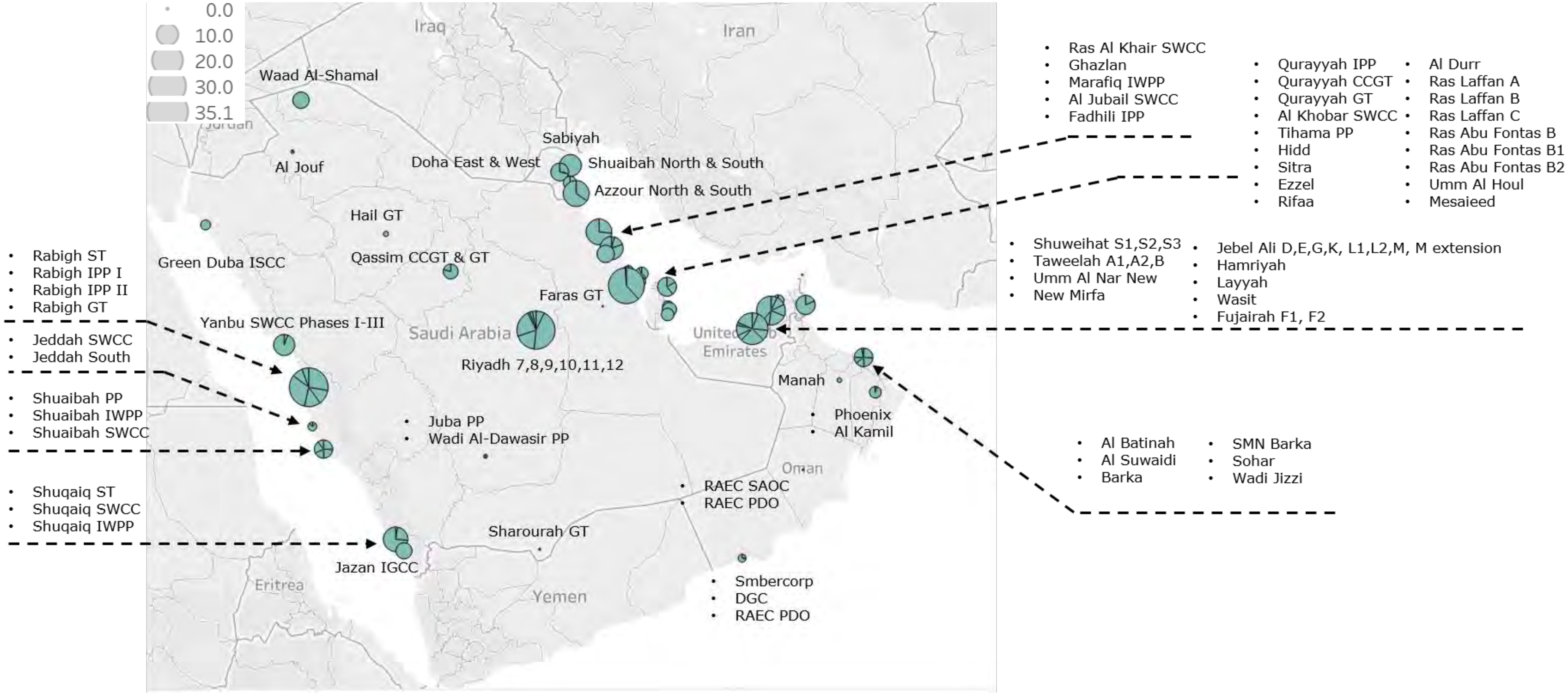


CO_2 PRODUCTION (Mt)



Only electricity generation from oil and natural gas

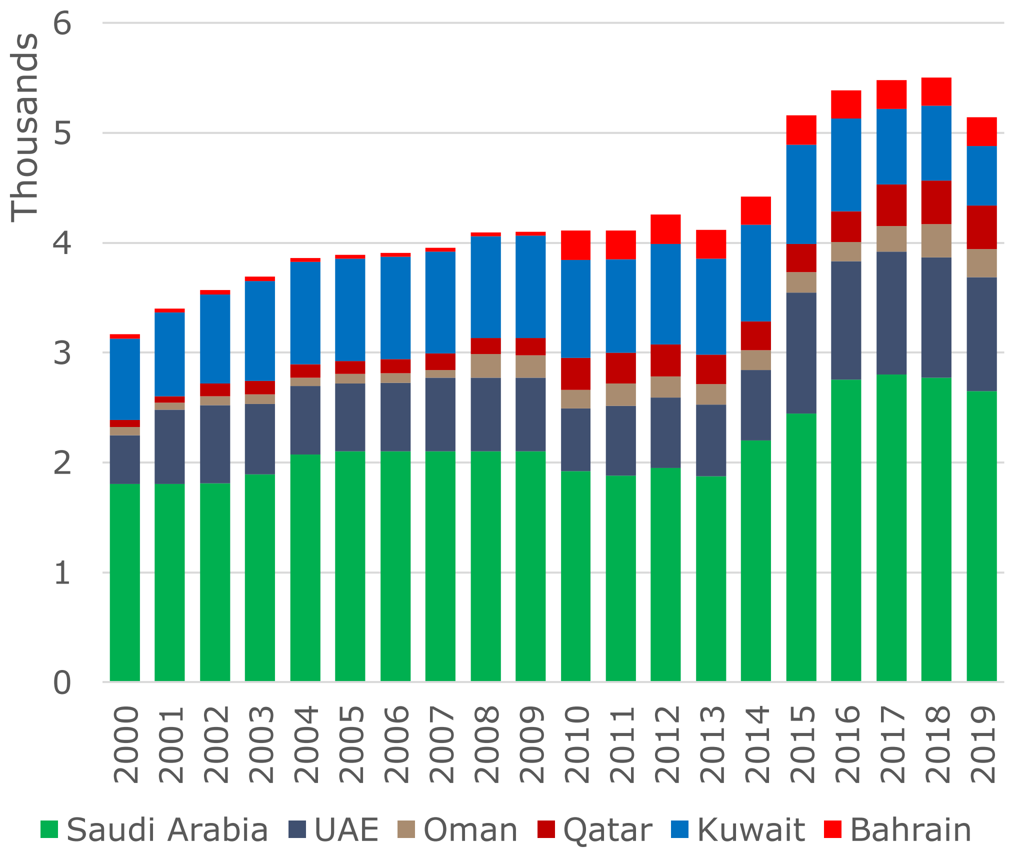
Power plant location – GCC*



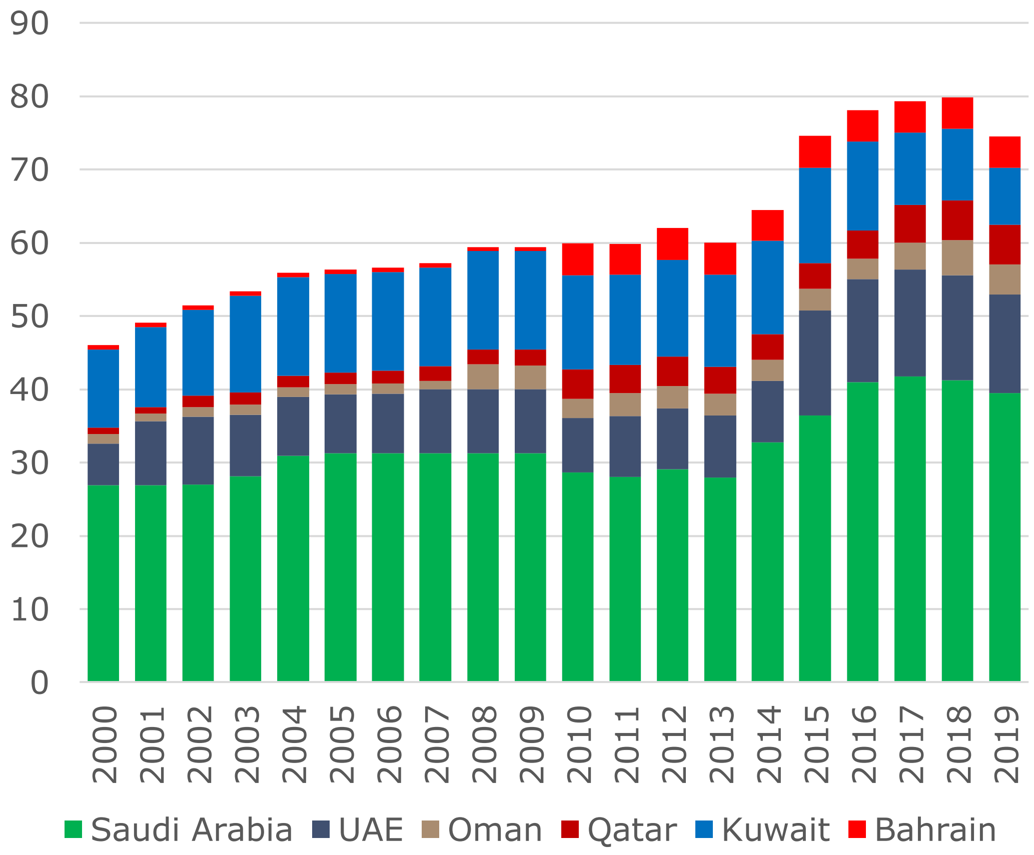
*Circle sizes are proportionate to CO_2 emissions ; any mismatches between the number of slices on a circle and the number of plant names owes to the presence of multiple phases of some plants

Historical oil refining

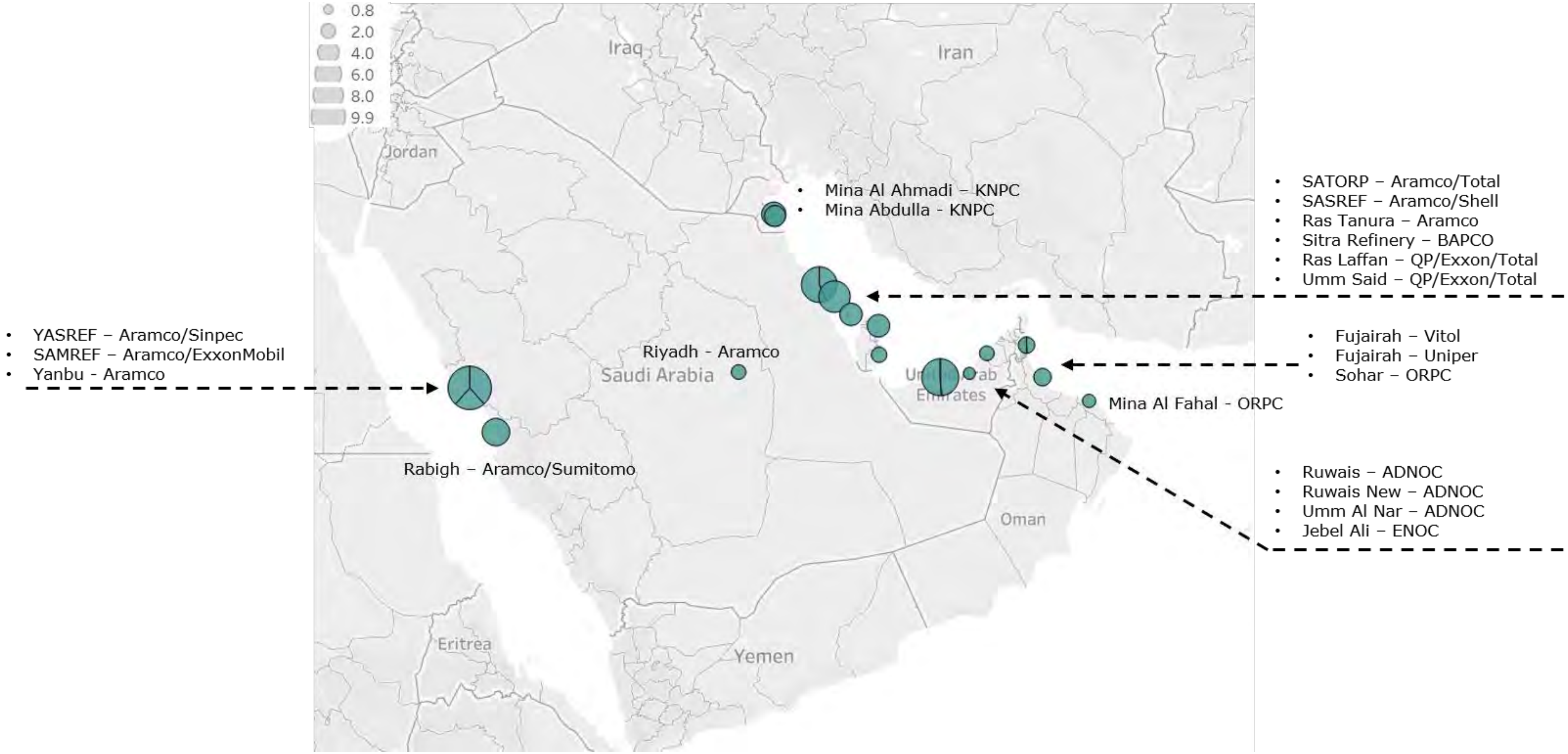
CRUDE OIL REFINING (THOUSAND BARRELS/DAY)



CO_2 PRODUCTION (Mt)



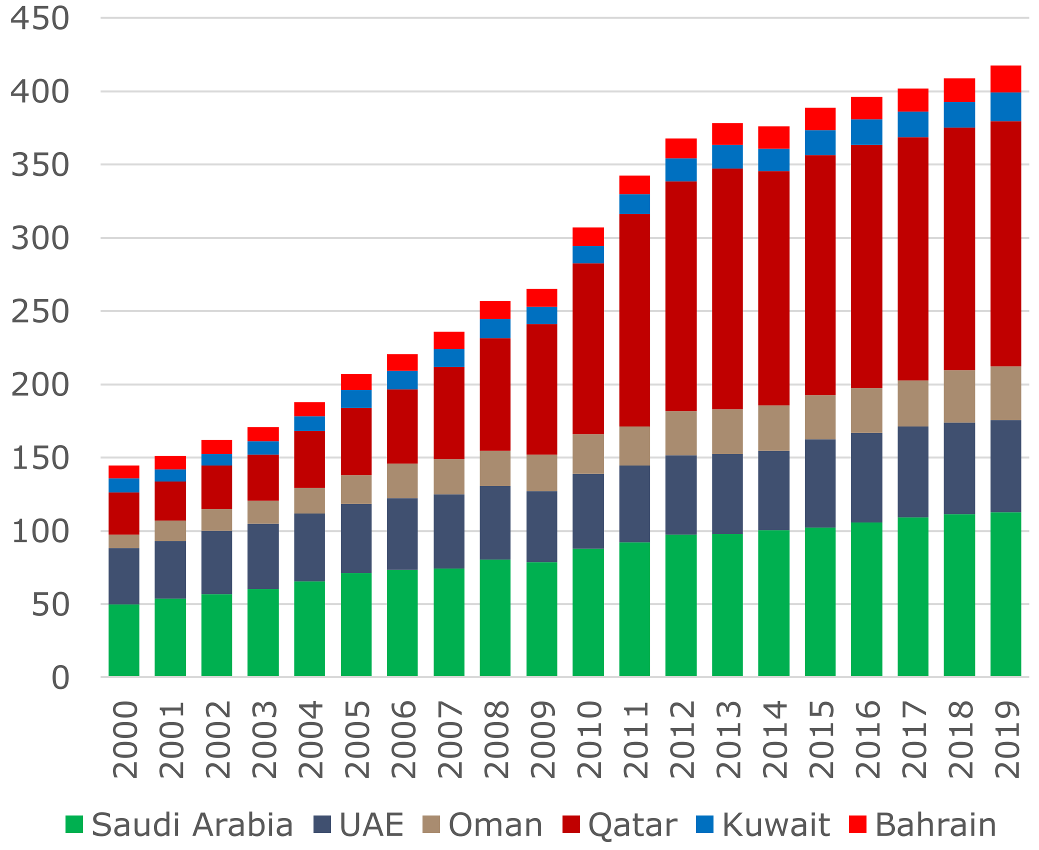
Oil refinery location – GCC*



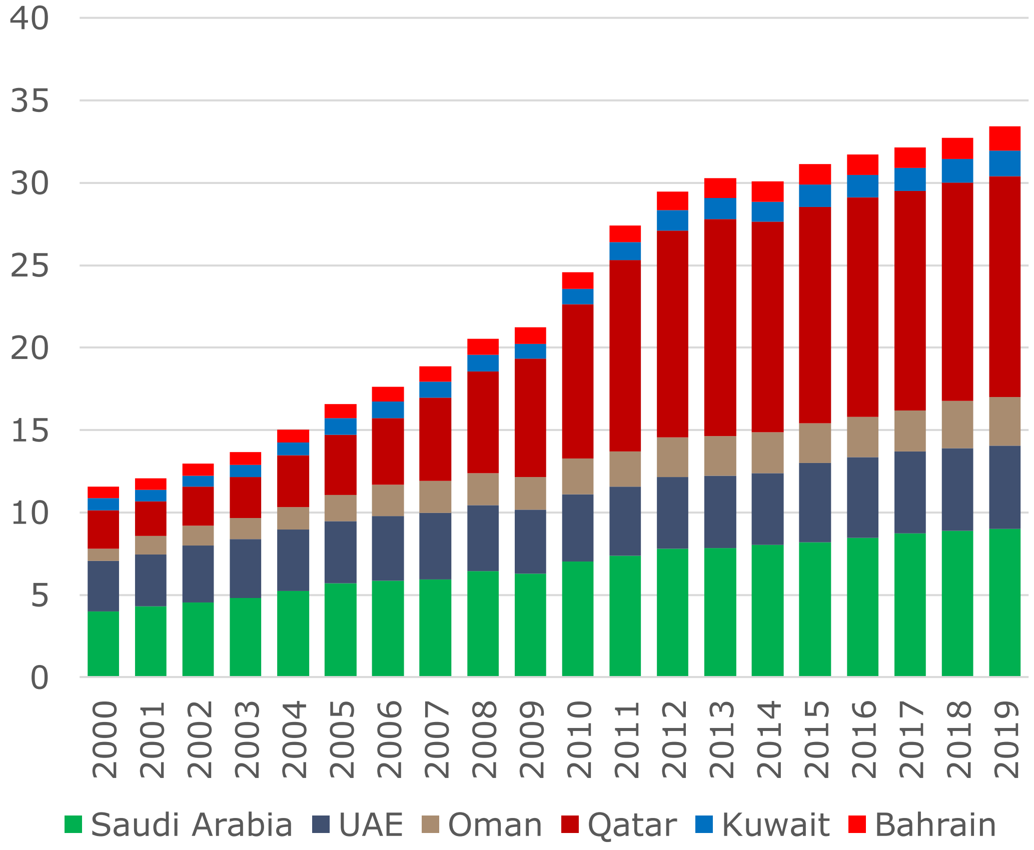
*Circle sizes are proportionate to CO_2 emissions ; any mismatches between the number of slices on a circle and the number of plant names owes to the presence of multiple phases of some plants

Historical natural gas processing

NATURAL GAS PRODUCTION (BCM)

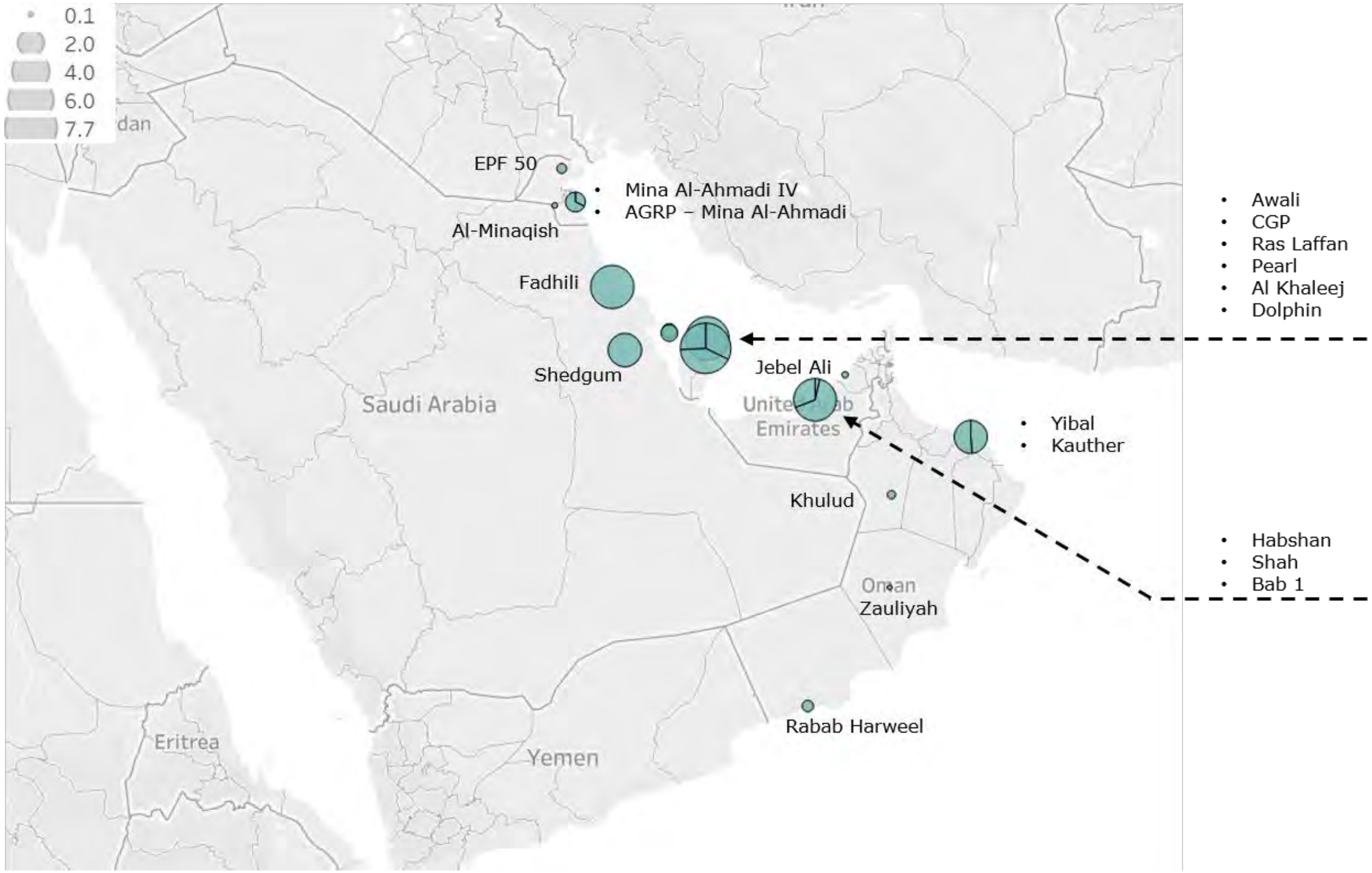


CO_2 PRODUCTION (Mt)



Source: EIA

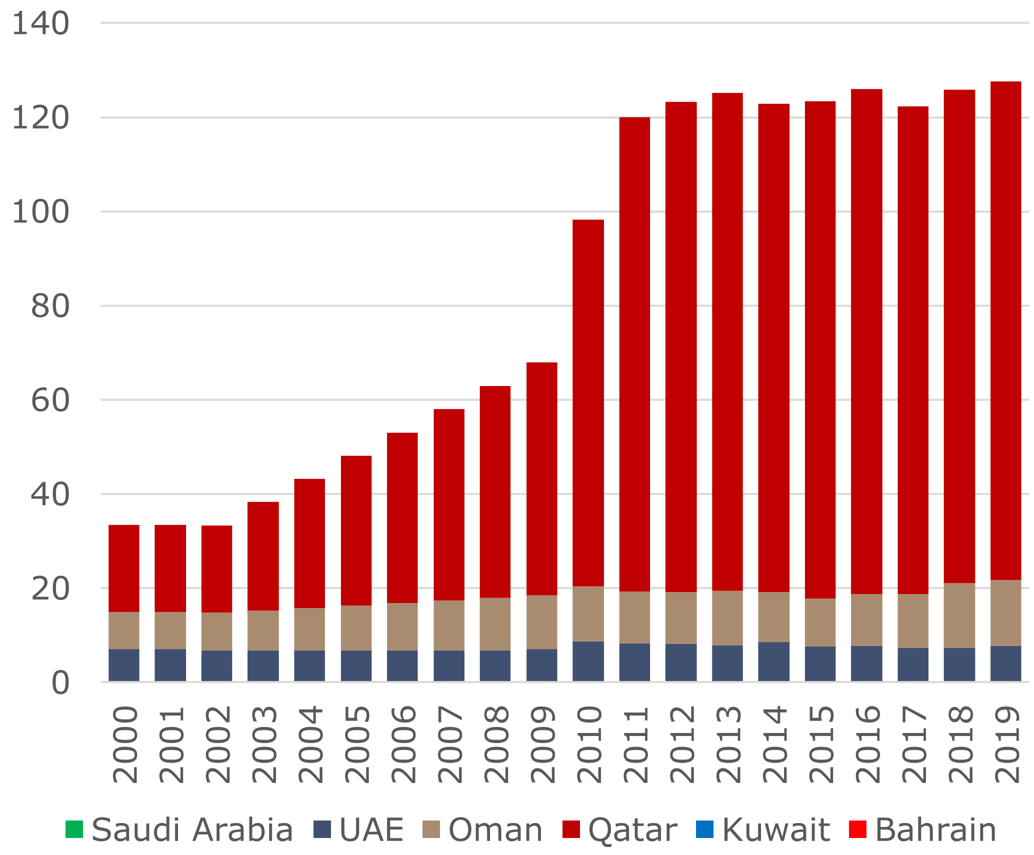
Natural gas processing plant location – GCC*



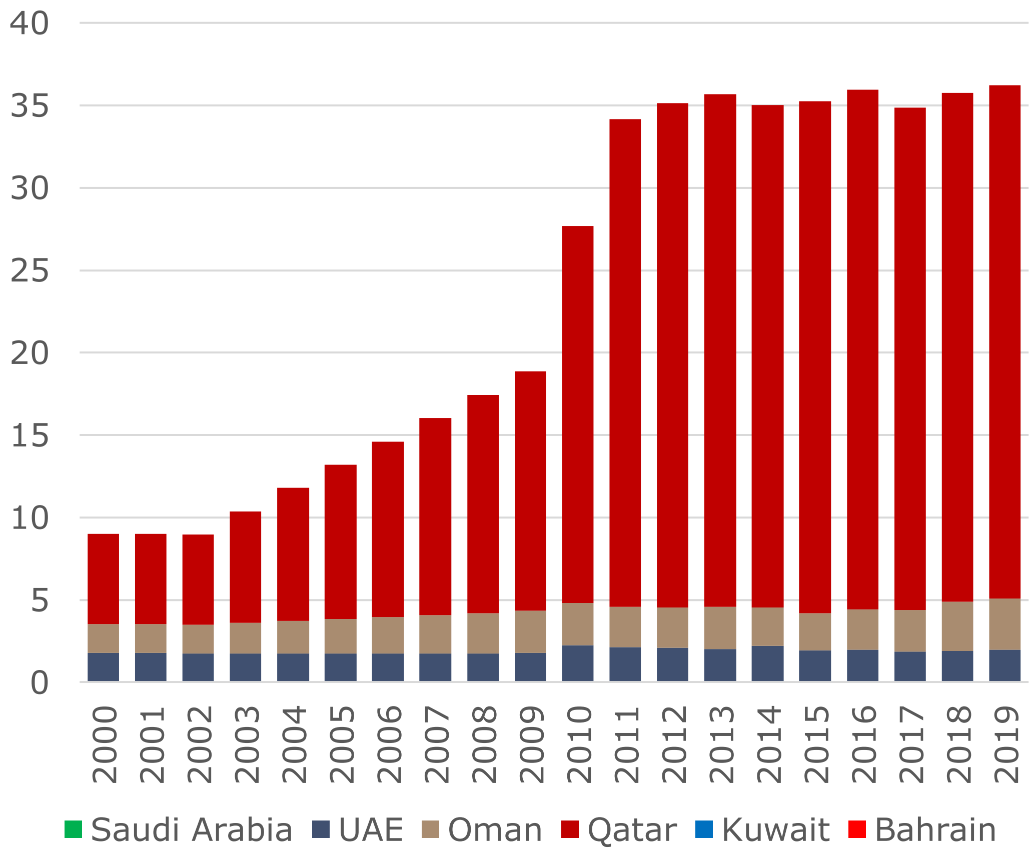
*Circle sizes are proportionate to CO_2 emissions ; any mismatches between the number of slices on a circle and the number of plant names owes to the presence of multiple phases of some plants

Historical LNG production

LNG PRODUCTION (BCM)



CO_2 PRODUCTION (Mt)



Source: GlobalData, USGS

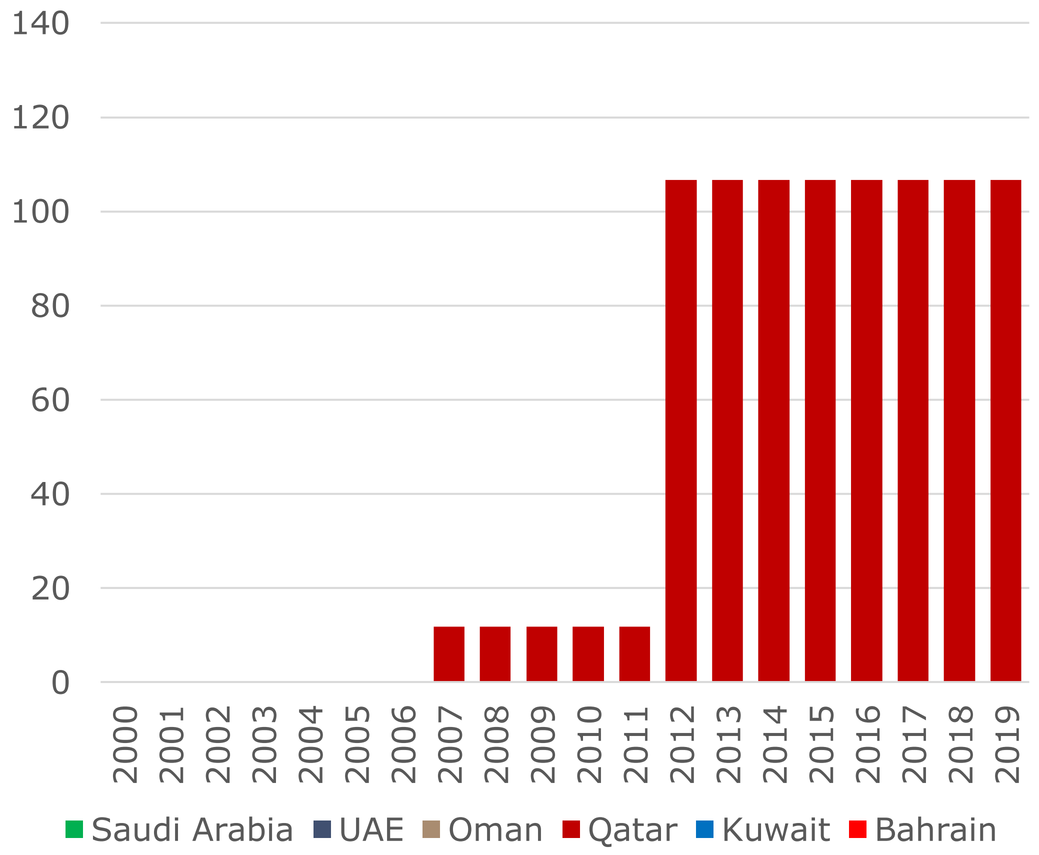
LNG plant location – GCC*

- Ras Laffan I
- Ras Laffan II
- Ras Laffan III
- Qatargas I
- Qatargas II-1
- Qatargas II-2
- Qatargas III
- Qatargas IV

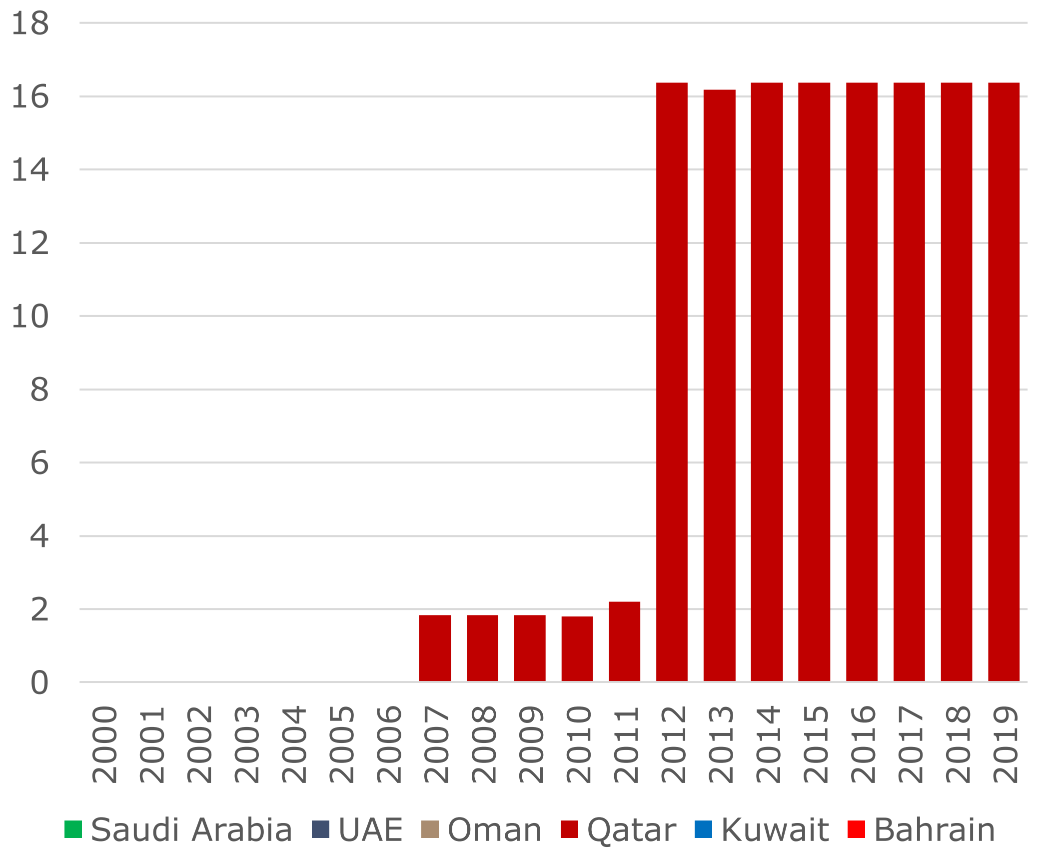
*Circle sizes are proportionate to CO_2 emissions ; any mismatches between the number of slices on a circle and the number of plant names owes to the presence of multiple phases of some plants

Historical GTL production

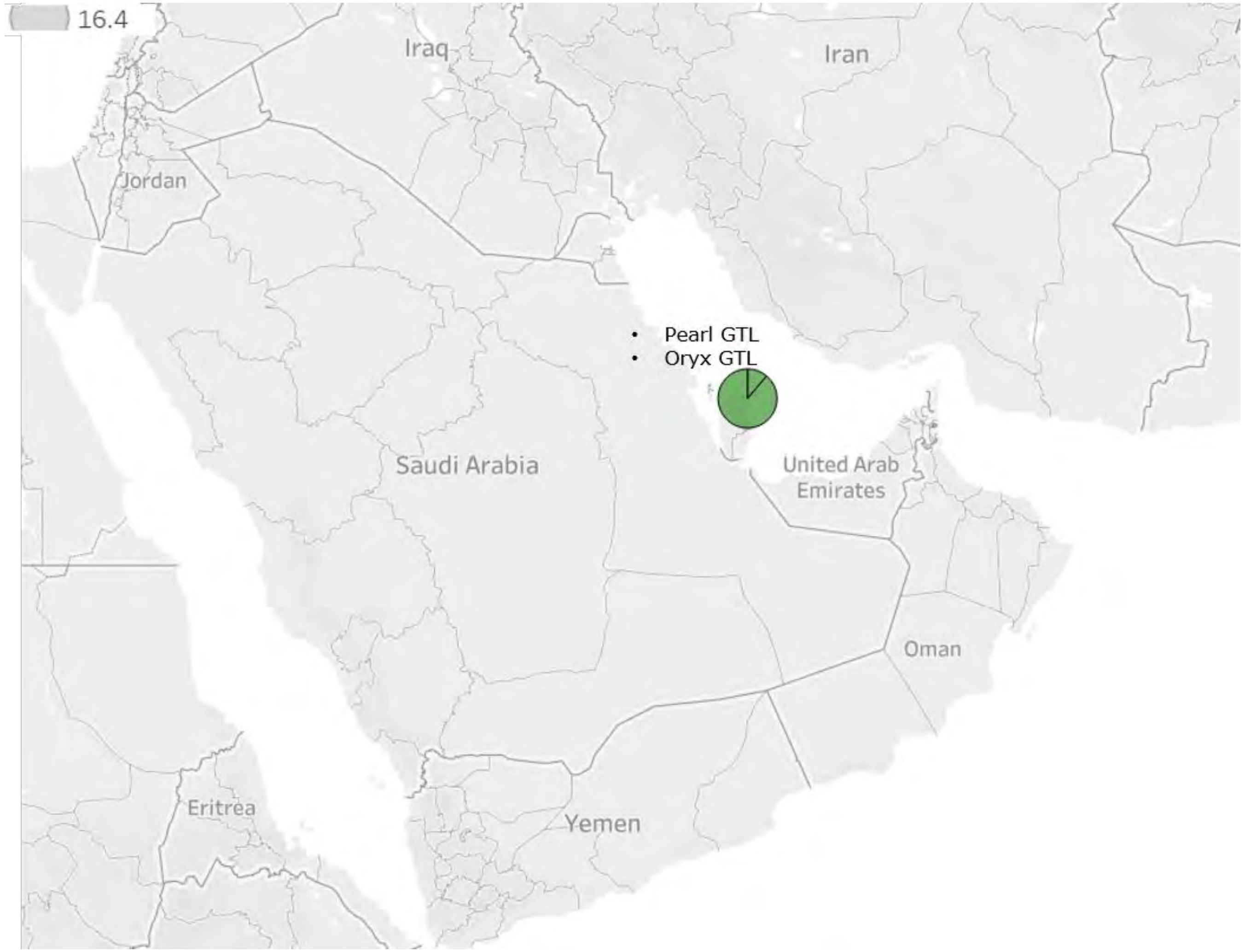
GTL PRODUCTION (BCM)



CO_2 PRODUCTION (Mt)



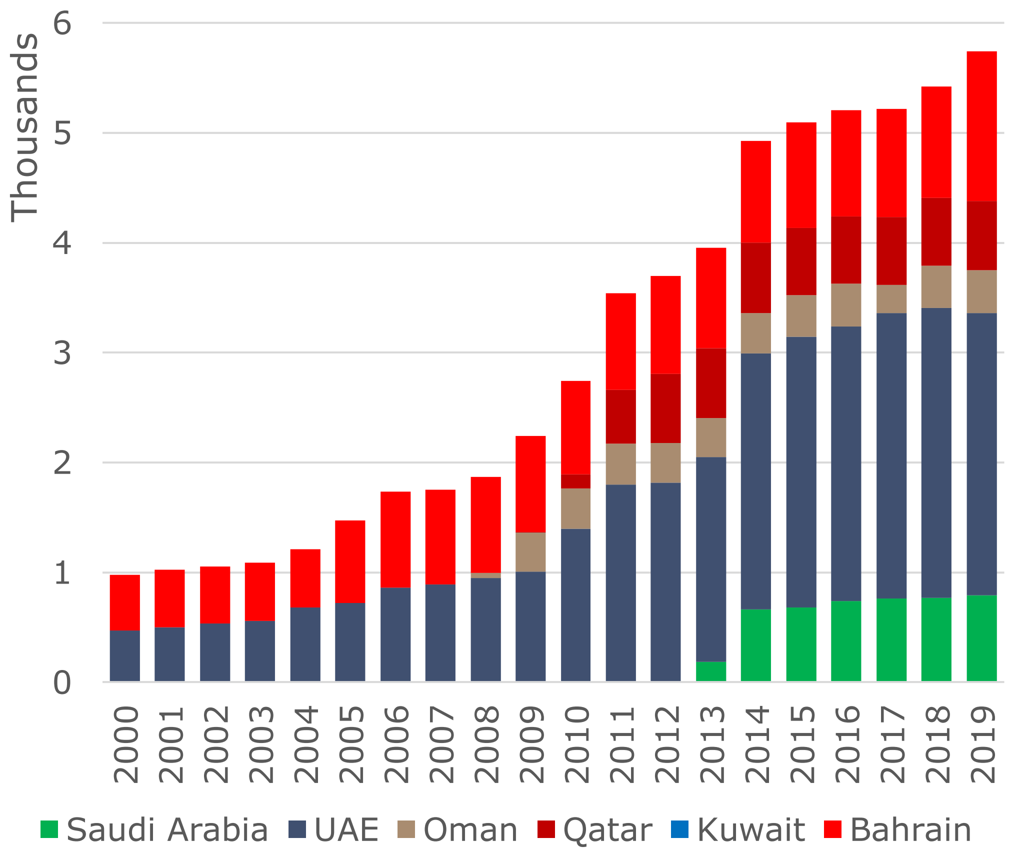
GTL plant location – GCC*



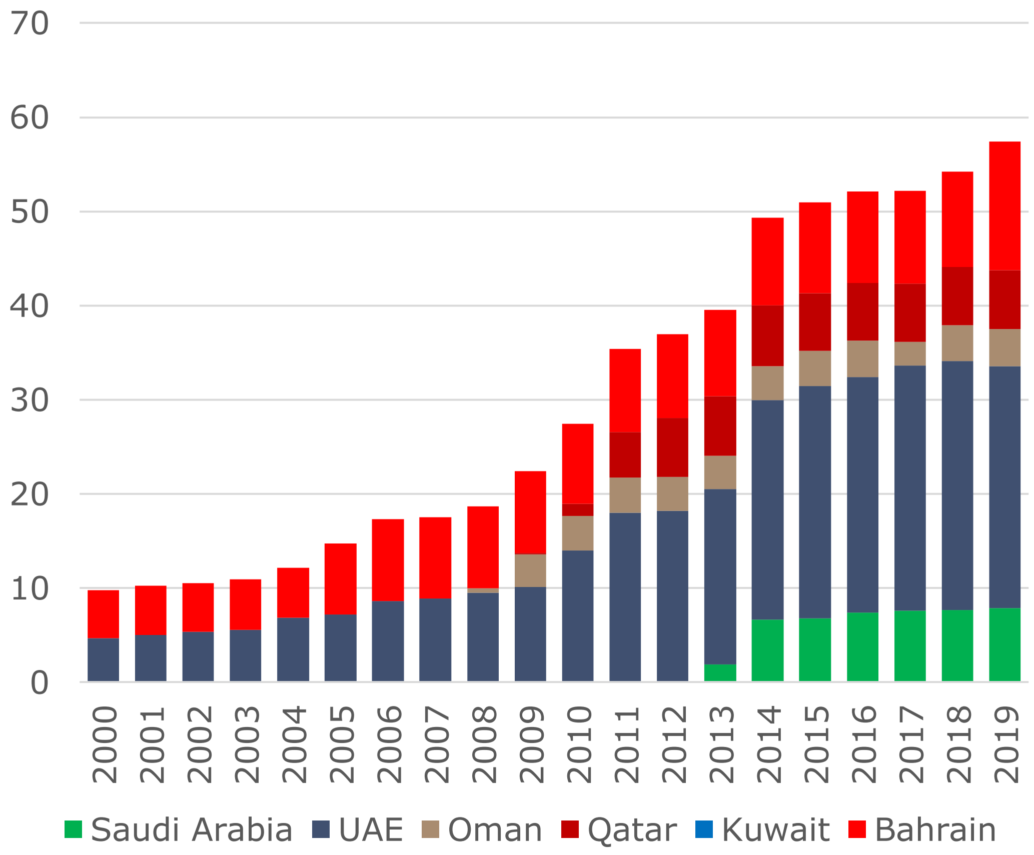
*Circle sizes are proportionate to CO_2 emissions ; any mismatches between the number of slices on a circle and the number of plant names owes to the presence of multiple phases of some plants

Historical aluminium production

ALUMINIUM PRODUCTION (kt)



CO_2 PRODUCTION (MT)



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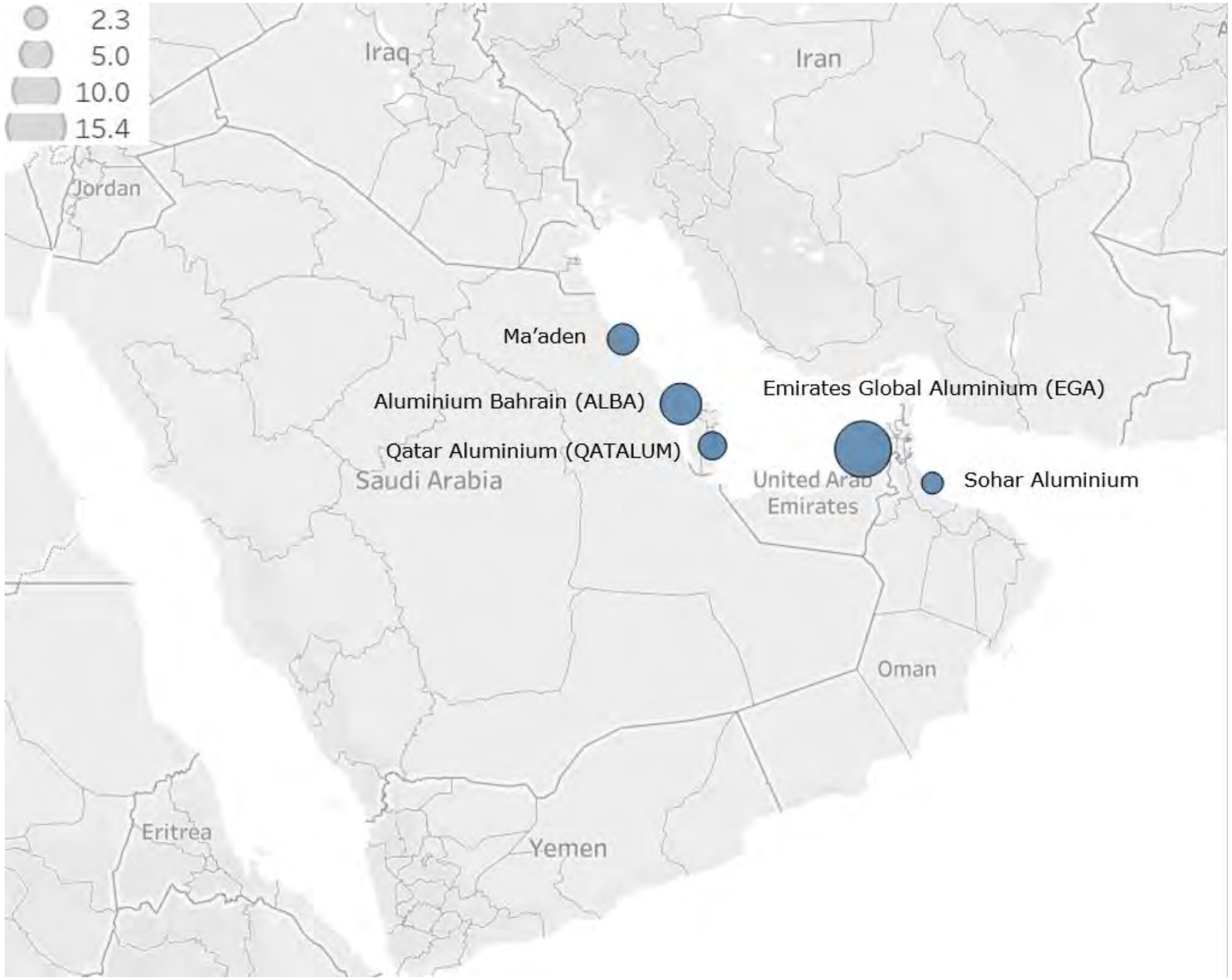
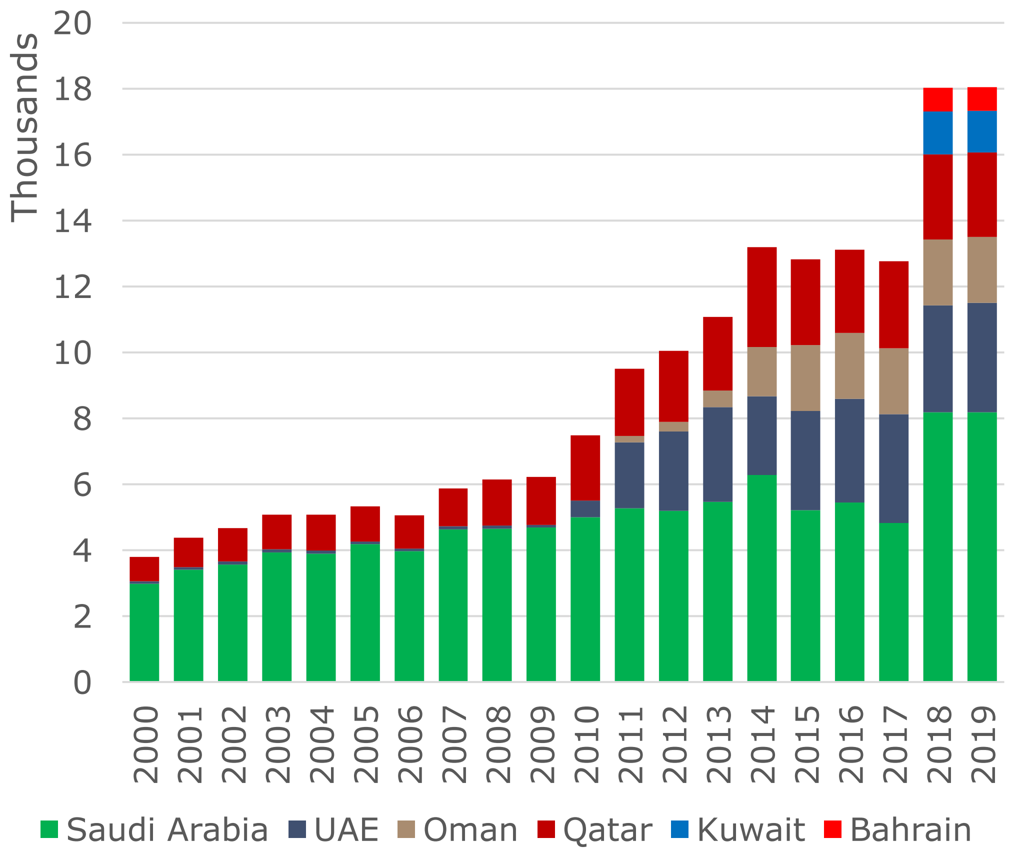
Aluminium plant location – GCC*



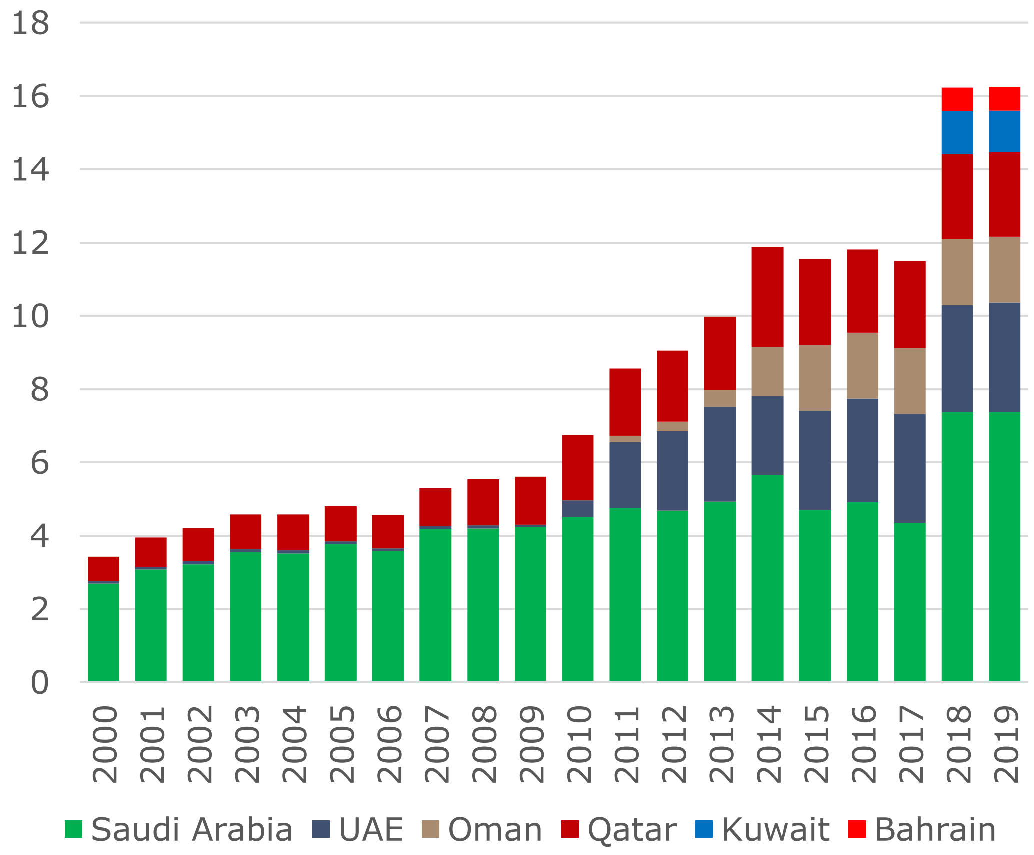
*Circle sizes are proportionate to CO_2 emissions ; any mismatches between the number of slices on a circle and the number of plant names owes to the presence of multiple phases of some plants

Historical iron and steel production

STEEL PRODUCTION (kt)



CO_2 PRODUCTION (Mt)



Iron & Steel plant location – GCC*

*Circle sizes are proportionate to CO_2 emissions ; any mismatches between the number of slices on a circle and the number of plant names owes to the presence of multiple phases of some plants

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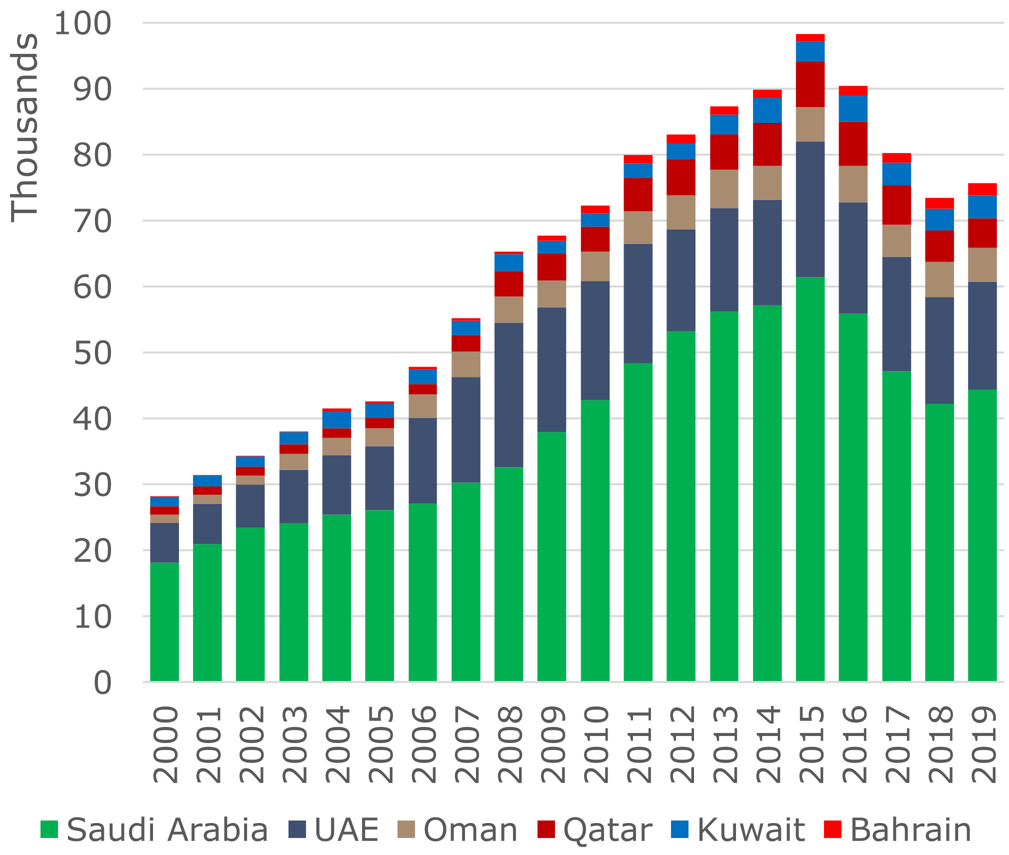
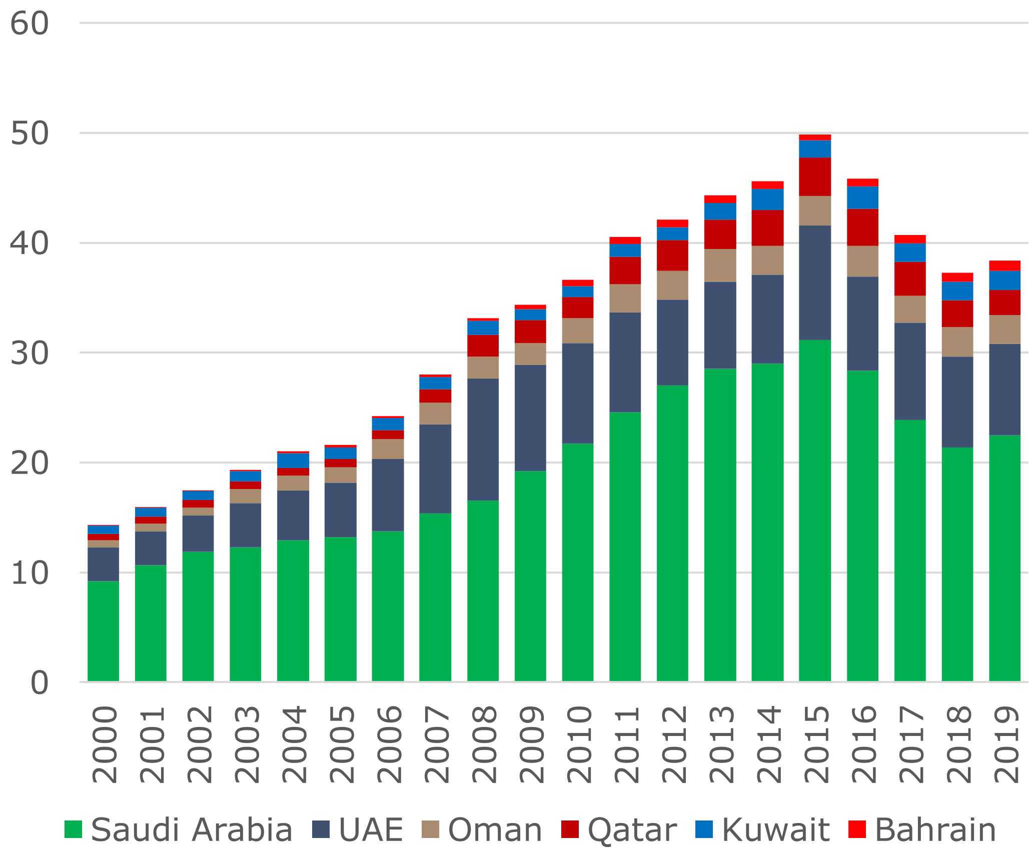
Historical cement production

CEMENT PRODUCTION (kt)

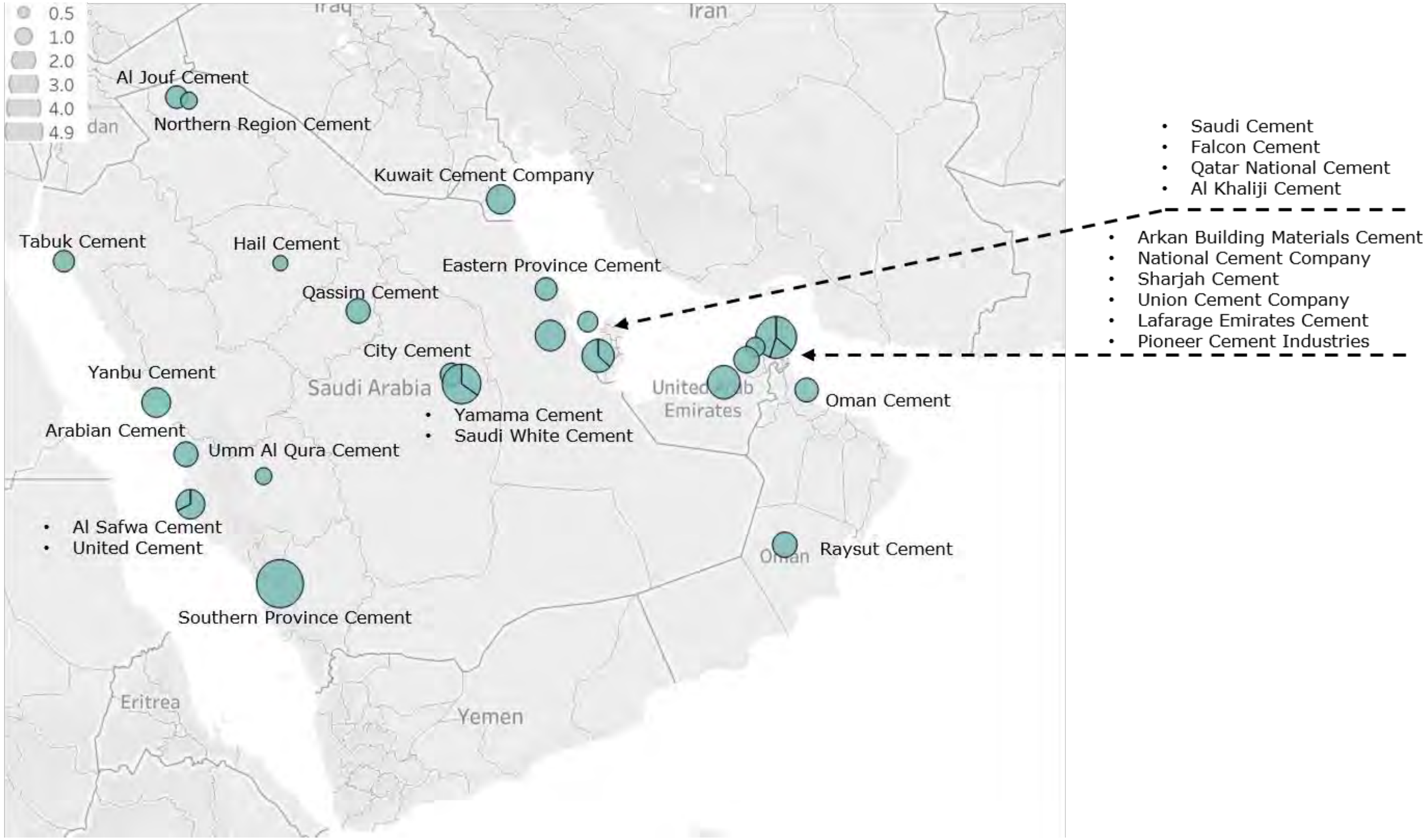


CO_2 PRODUCTION (Mt)



Source: Cement Production USGS Cement Statistics

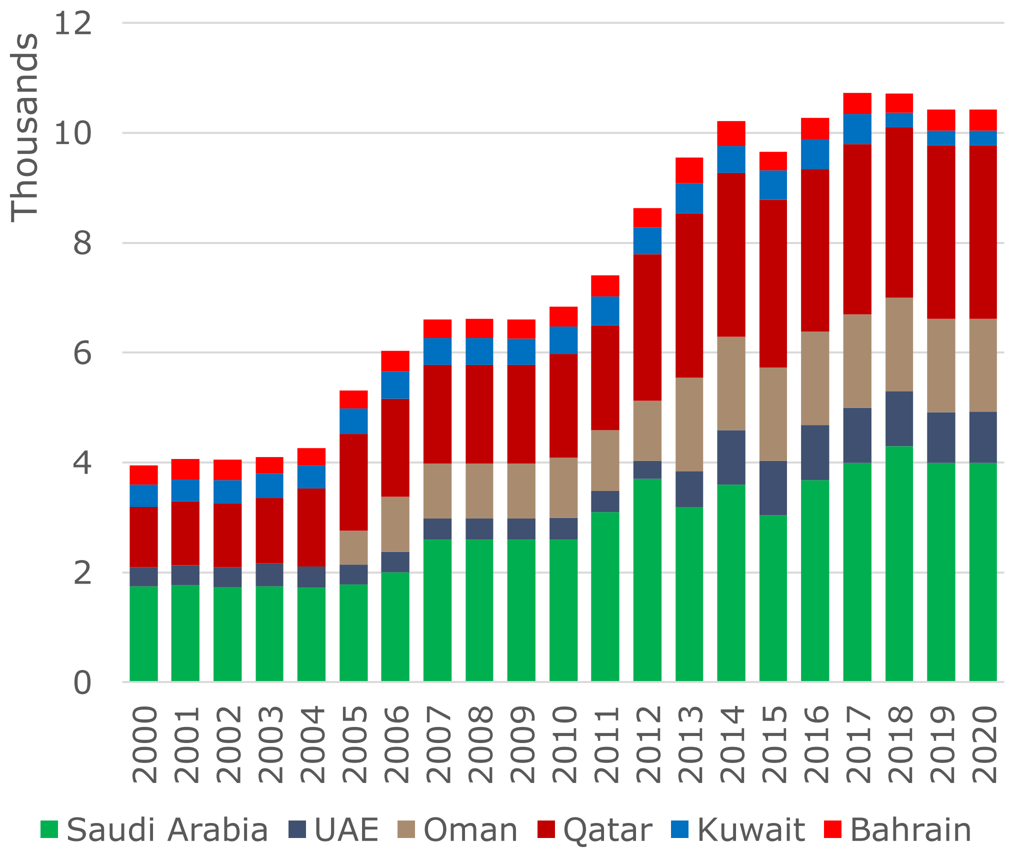
Cement plant locations – GCC*



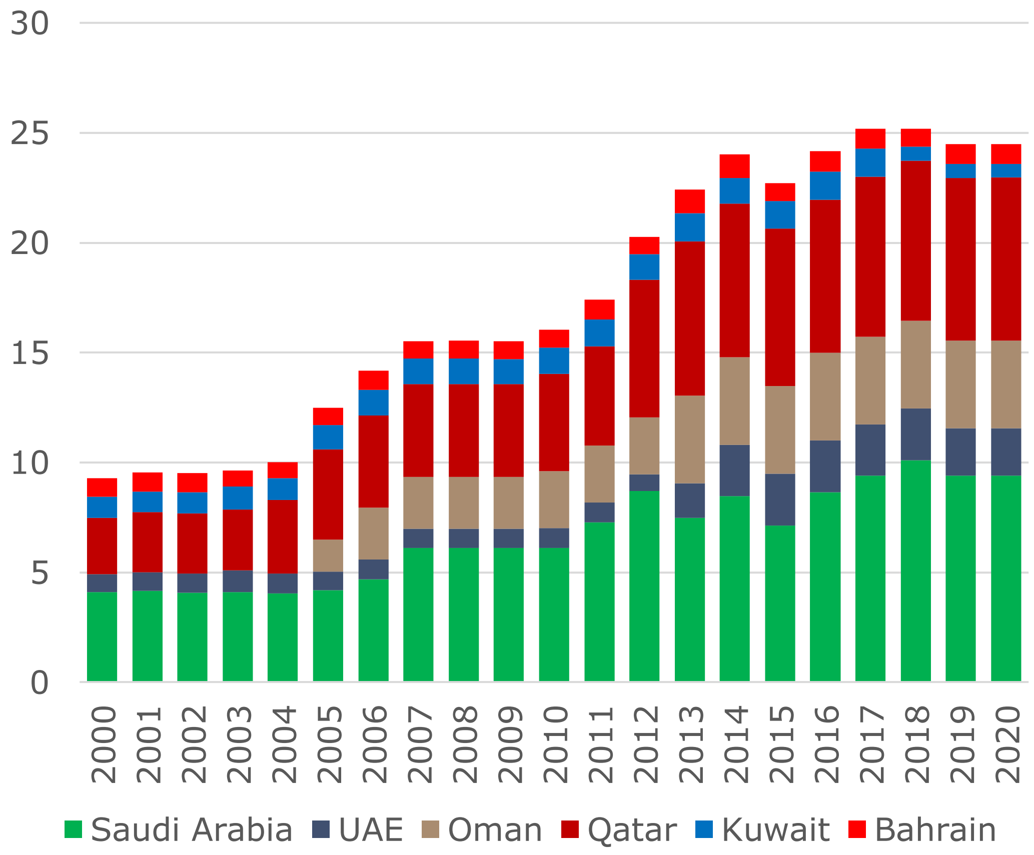
*Circle sizes are proportionate to CO_2 emissions ; any mismatches between the number of slices on a circle and the number of plant names owes to the presence of multiple phases of some plants

Historical fertilisers production

FERTILISERS PRODUCTION (kt)

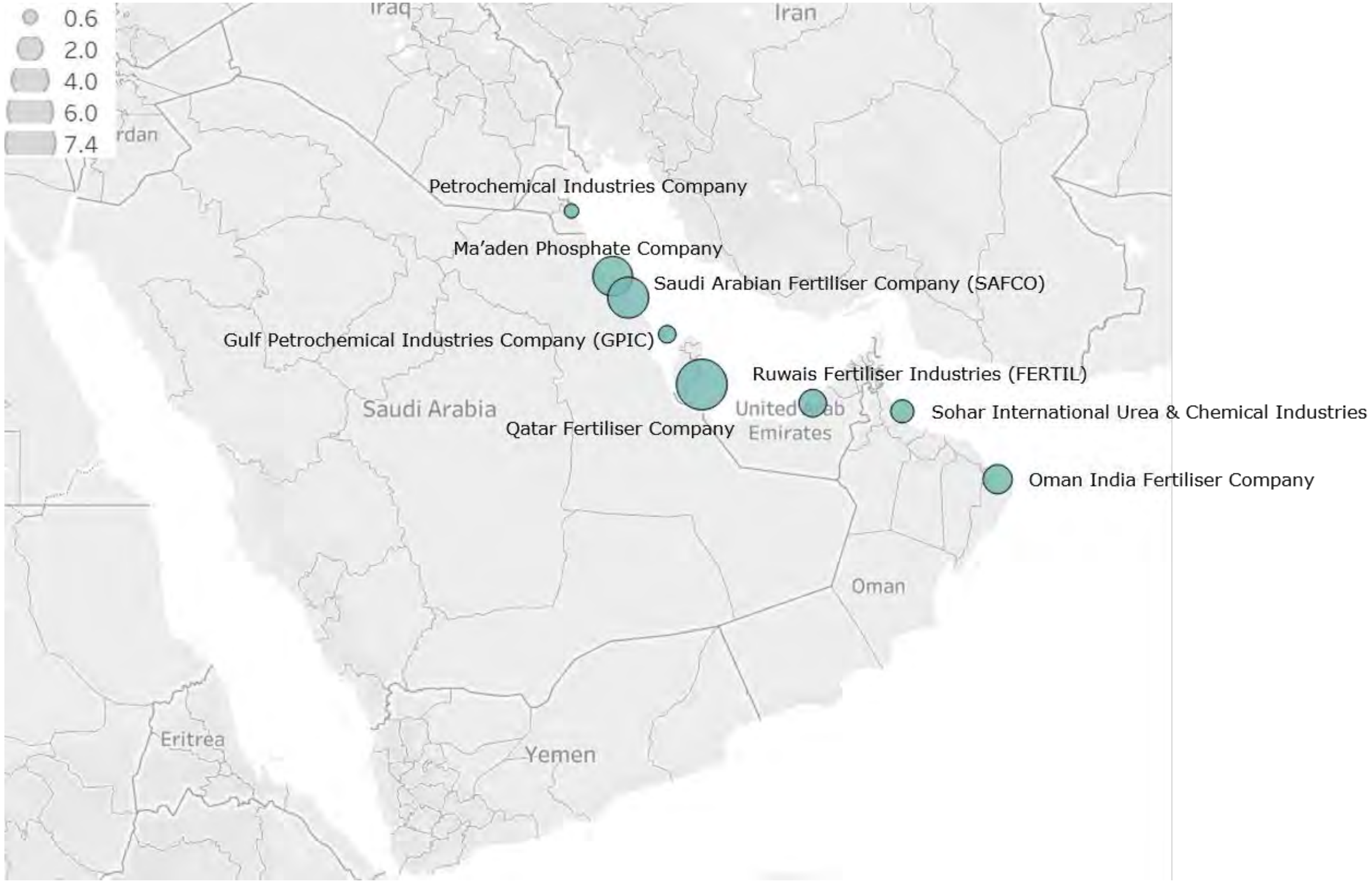


CO_2 PRODUCTION (Mt)



Gaffney Cline AFRY ÅF PÖYRY

Fertilisers plant location – GCC*



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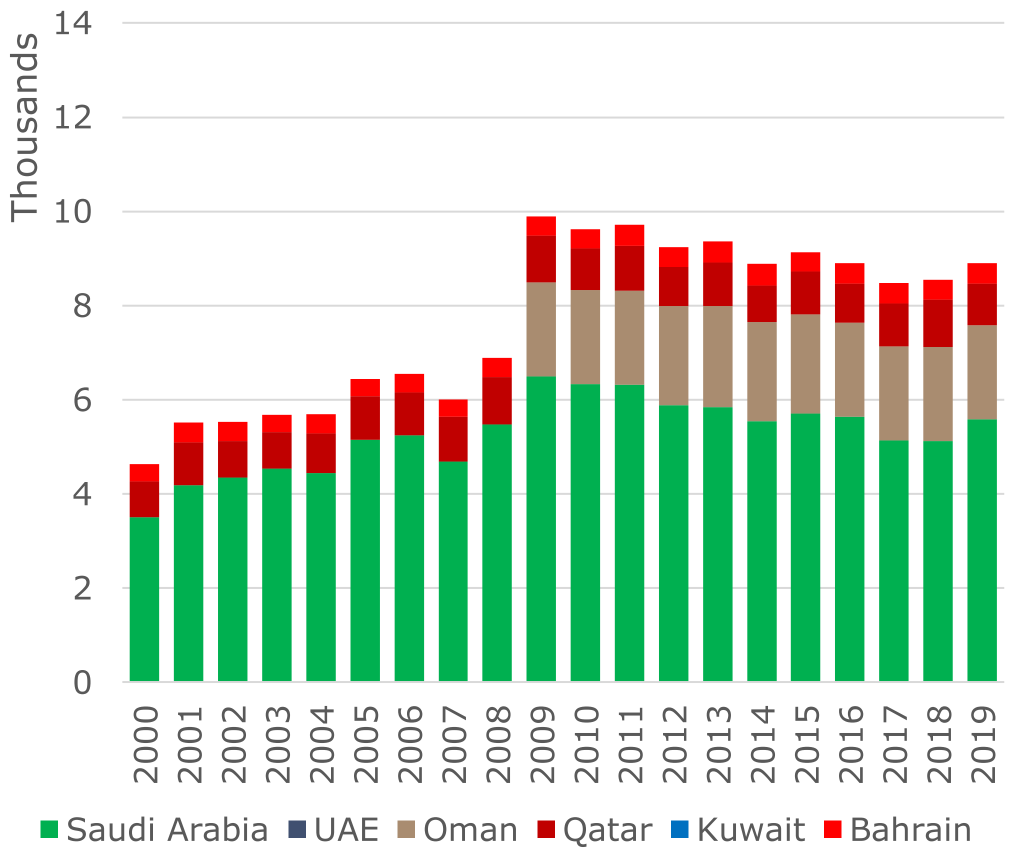
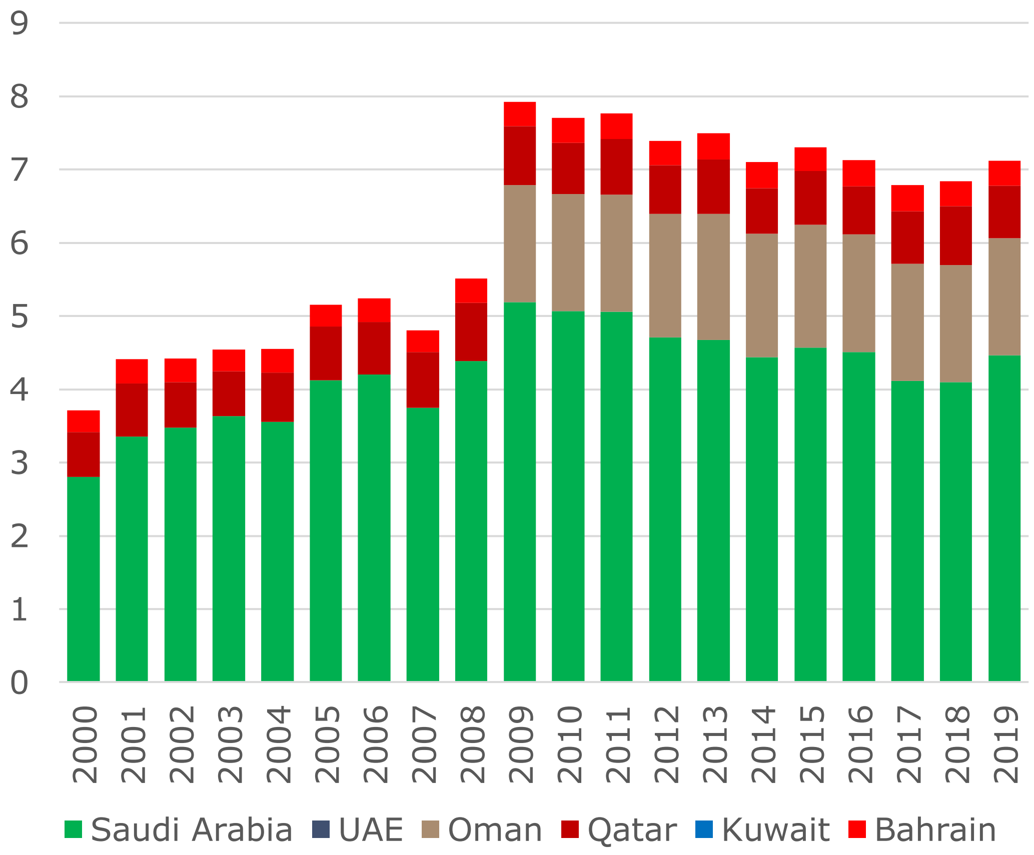
Historical methanol production

METHANOL PRODUCTION (kt)



CO_2 PRODUCTION (Mt)



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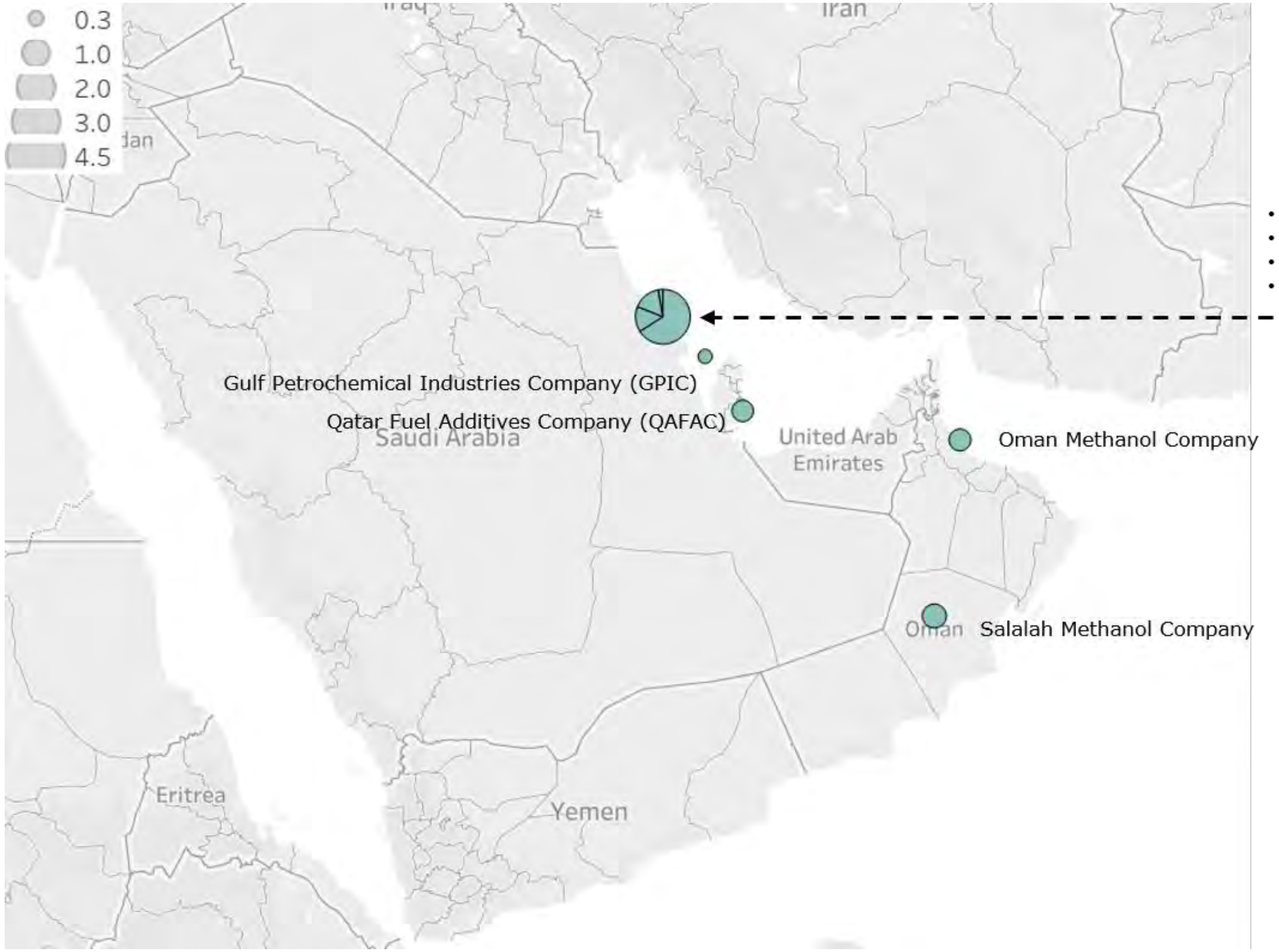
Methanol plant location – GCC*

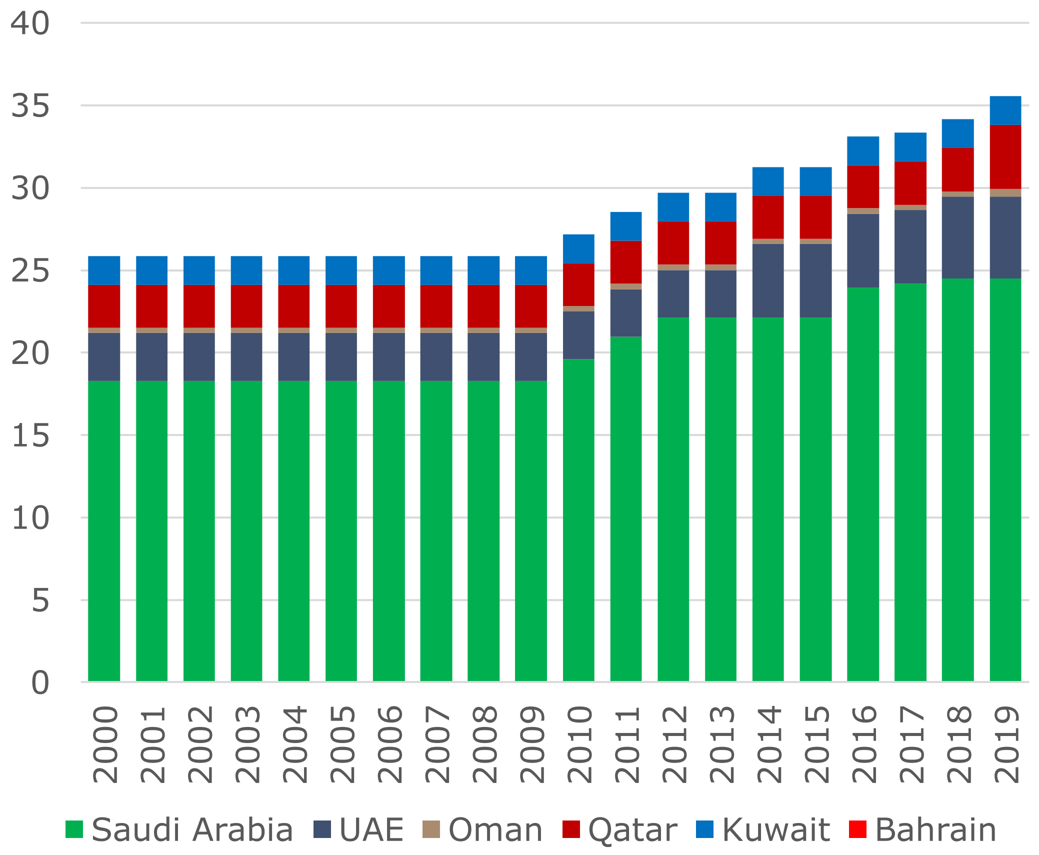


- Arrazi Saudi Methanol Company
- Ibn Sina
- International Methanol Company
- Methanol Chemical Company

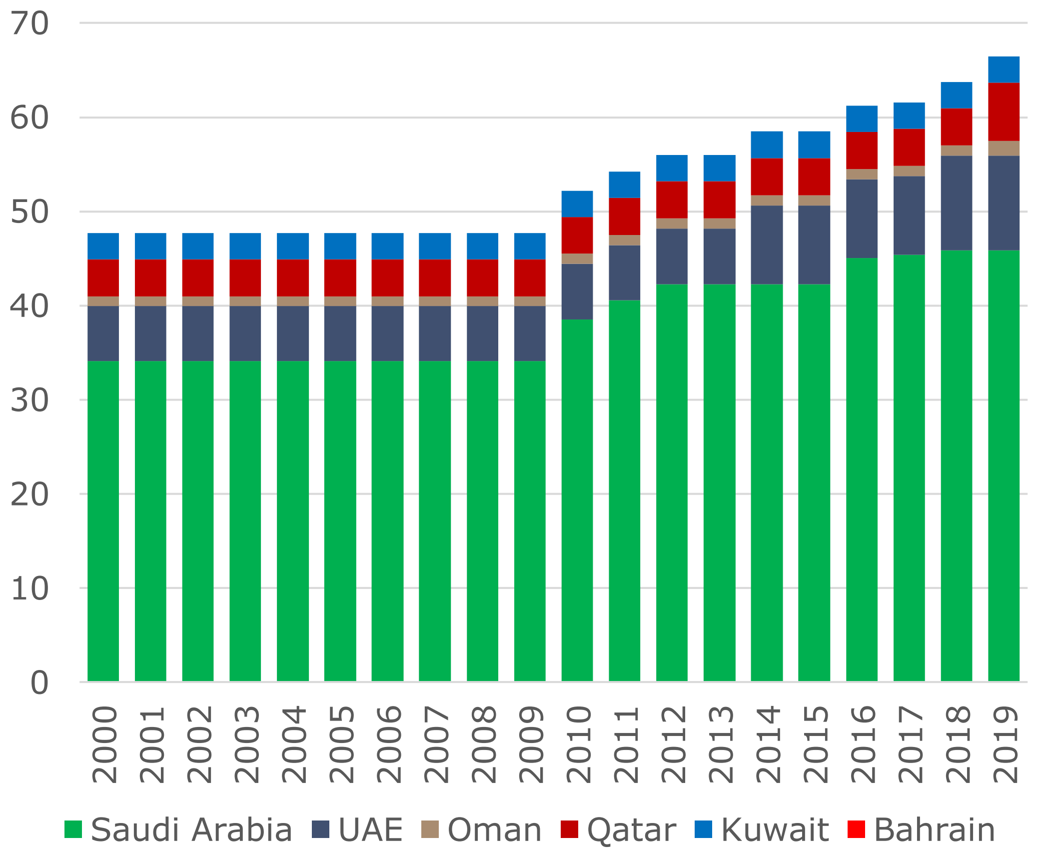
*Circle sizes are proportionate to CO_2 emissions ; any mismatches between the number of slices on a circle and the number of plant names owes to the presence of multiple phases of some plants

Historical petrochemicals production

PETROCHEMICALS PRODUCTION (kt)



CO_2 PRODUCTION (Mt)



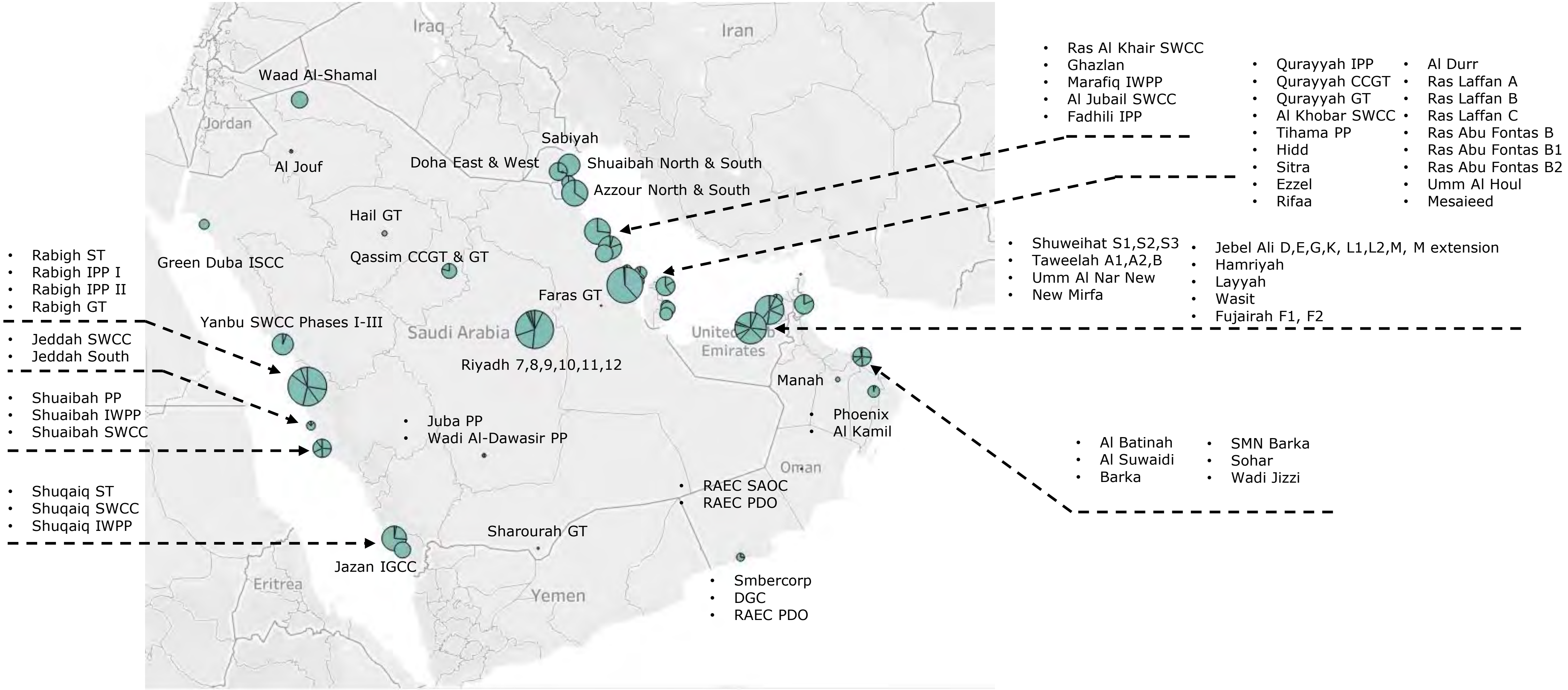
Source: Cement Production USGS Cement Statistics

Petrochemical plants location – GCC*

*Circle sizes are proportionate to CO_2 emissions ; any mismatches between the number of slices on a circle and the number of plant names owes to the presence of multiple phases of some plants

Gaffney Cline AFRY ÅF PÖYRY

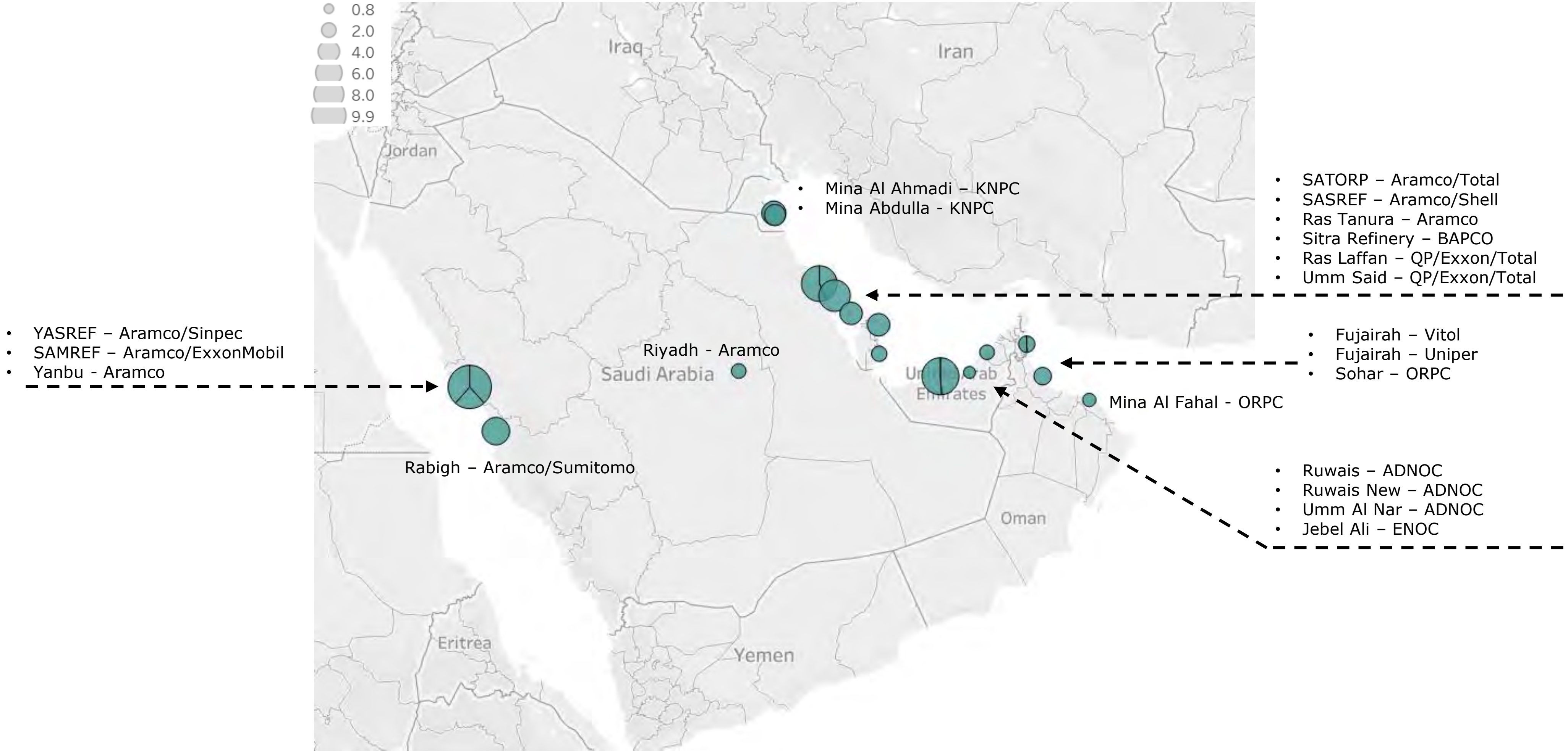
Power plant location – GCC*



*Circle sizes are proportionate to CO_2 emissions ; any mismatches between the number of circle constituents and plant names owes to the presence of multiple phases of some plants

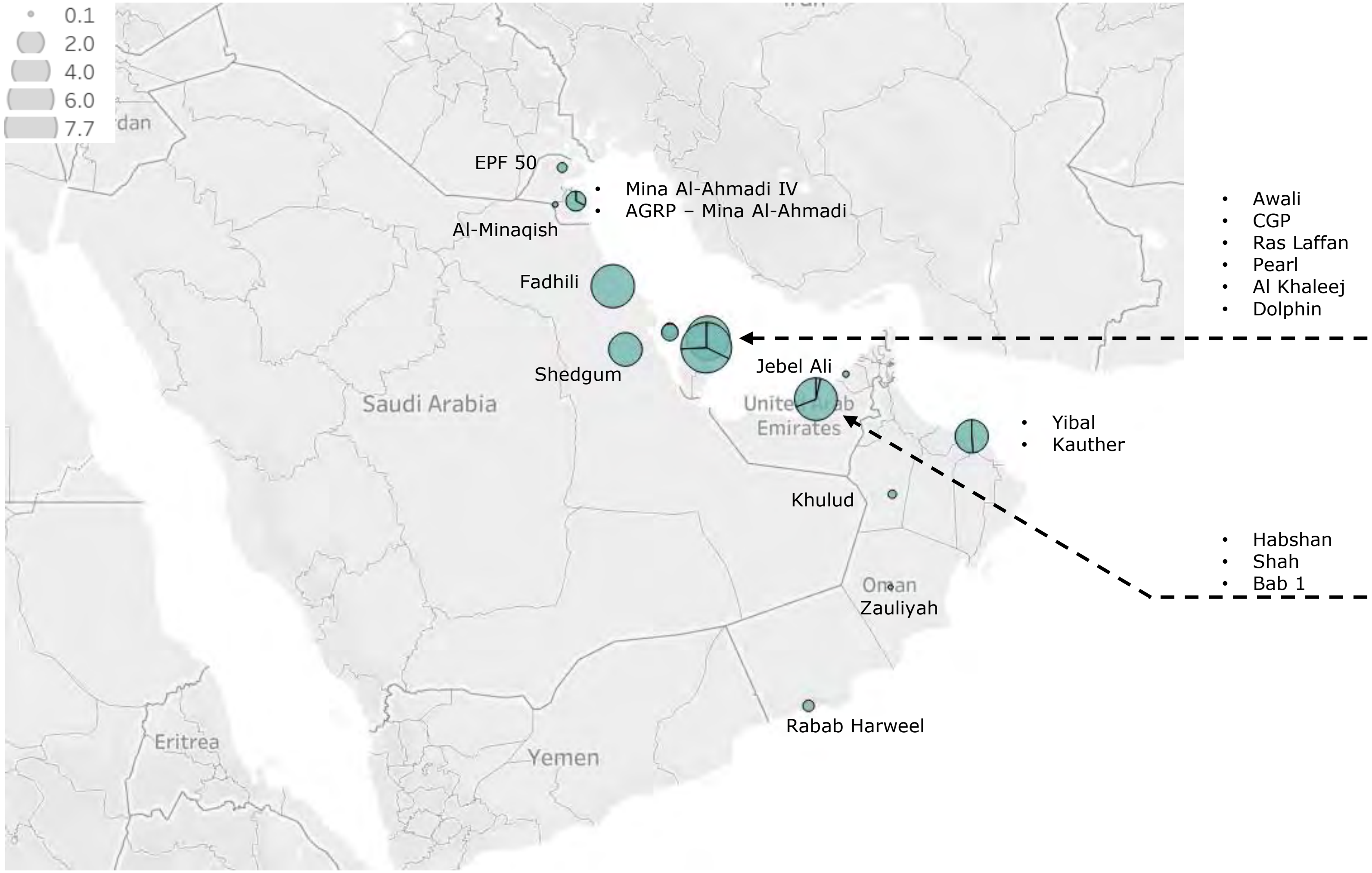
Gaffney Cline AFRY ÅF PÖYRY

Oil refinery location – GCC*



*Circle sizes are proportionate to CO_2 emissions ; any mismatches between the number of slices on a circle and the number of plant names owes to the presence of multiple phases of some plants

Natural gas processing plant location – GCC*



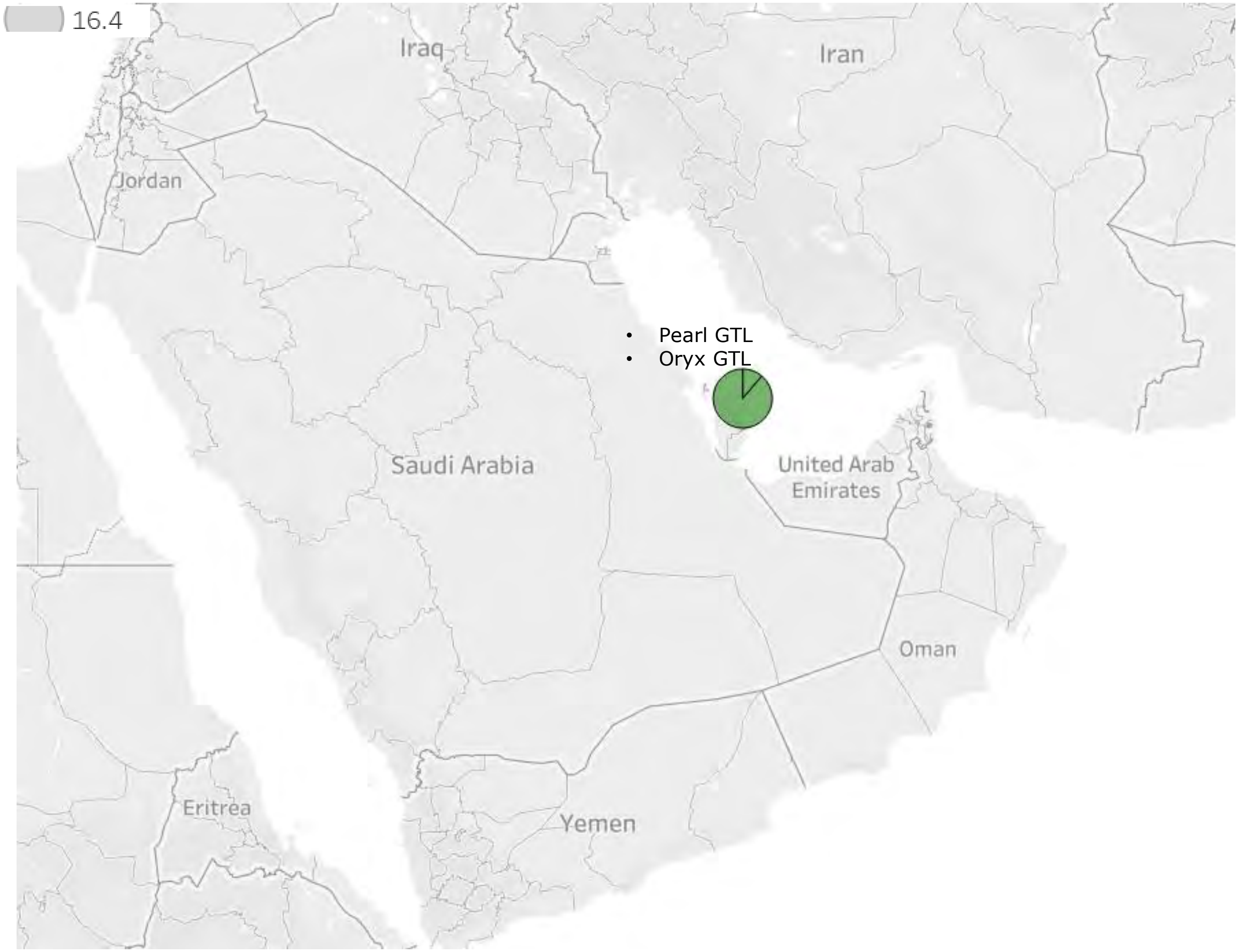
*Circle sizes are proportionate to CO_2 emissions ; any mismatches between the number of slices on a circle and the number of plant names owes to the presence of multiple phases of some plants

Gaffney Cline AFRY ÅF PÖYRY

LNG plant location – GCC*

*Circle sizes are proportionate to CO_2 emissions ; any mismatches between the number of slices on a circle and the number of plant names owes to the presence of multiple phases of some plants

GTL plant location – GCC*



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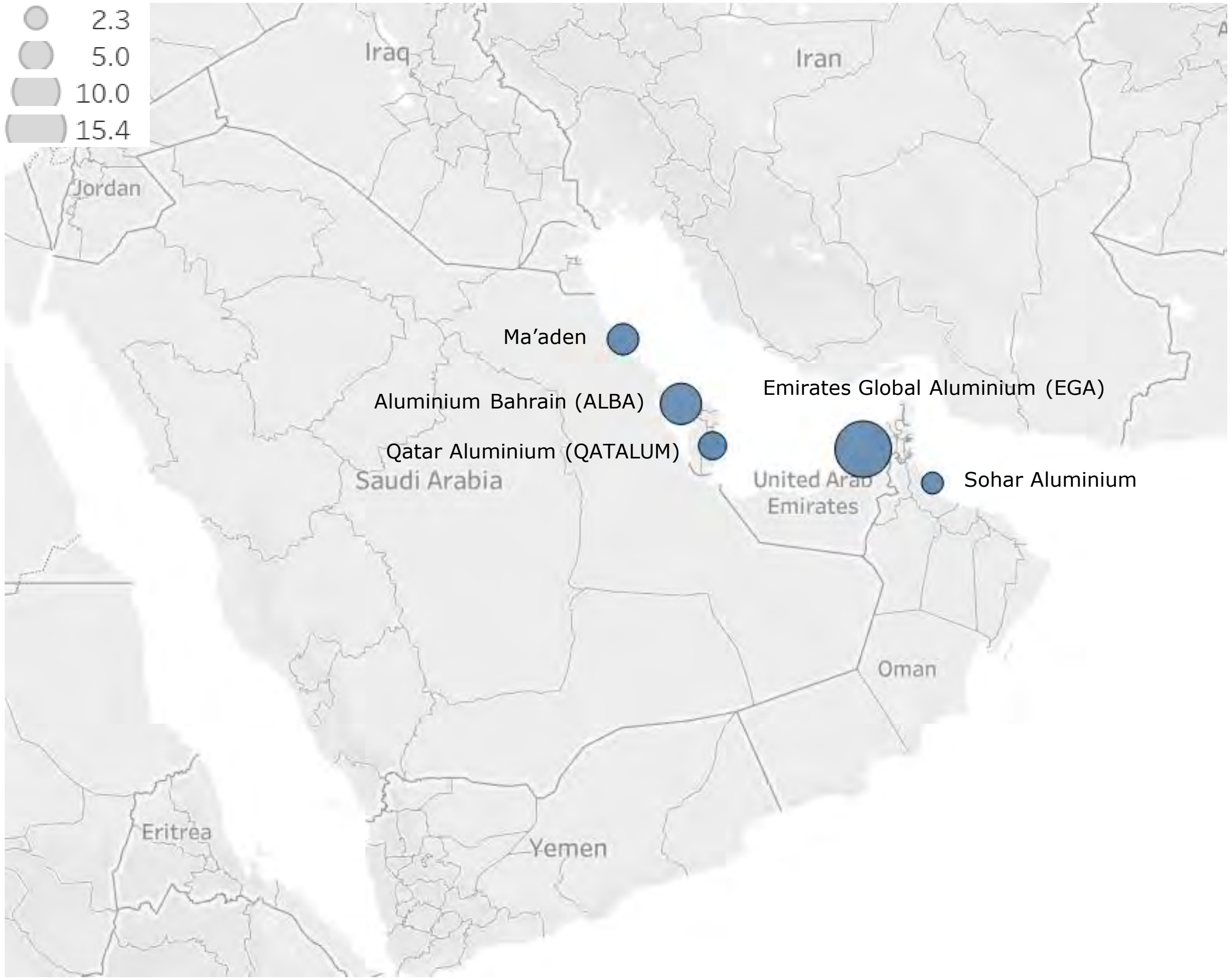
Aluminium plant location – GCC*

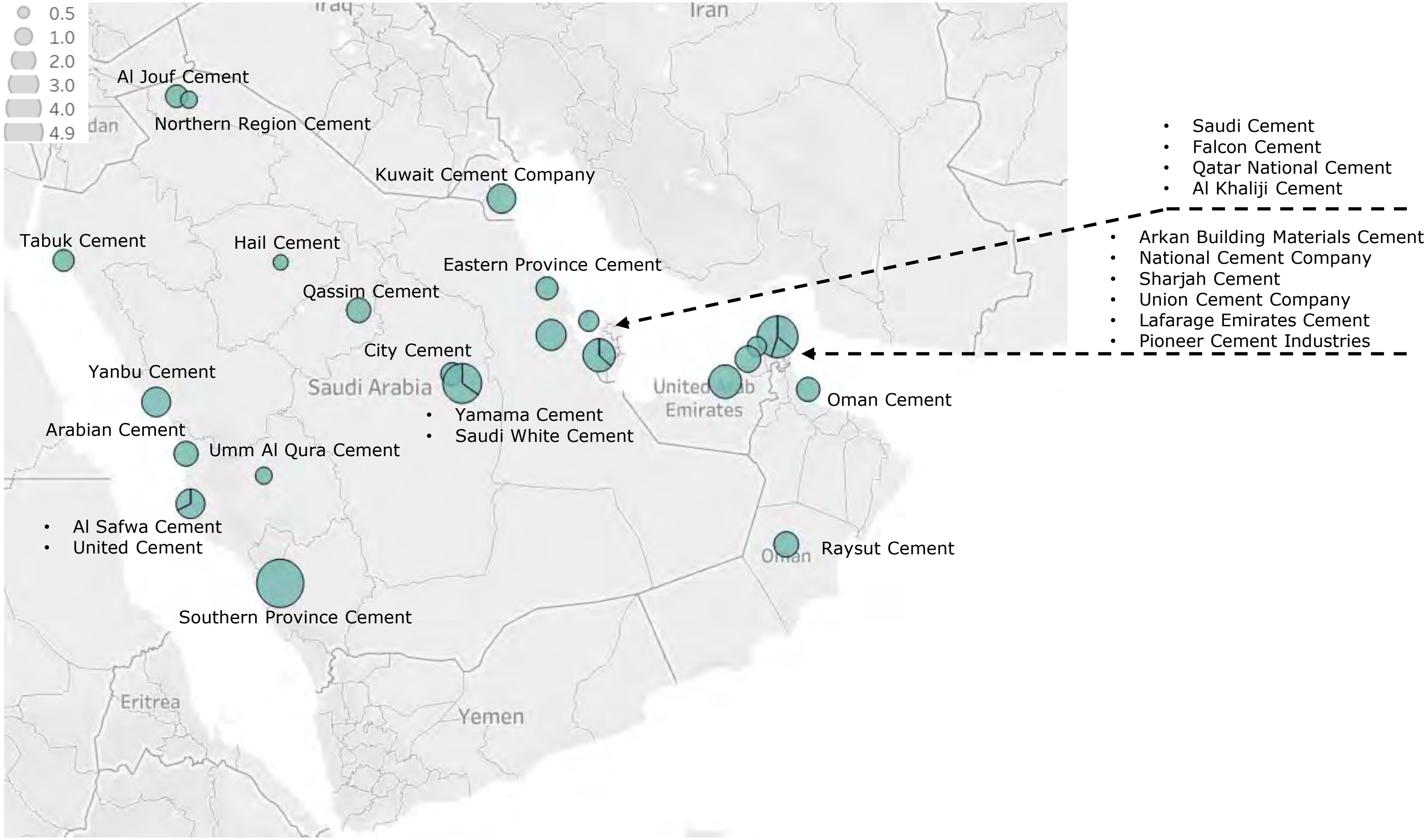


*Circle sizes are proportionate to CO_2 emissions ; any mismatches between the number of slices on a circle and the number of plant names owes to the presence of multiple phases of some plants

Iron & Steel plant location – GCC*

*Circle sizes are proportionate to CO_2 emissions ; any mismatches between the number of slices on a circle and the number of plant names owes to the presence of multiple phases of some plants

Cement plant locations – GCC*



*Circle sizes are proportionate to CO_2 emissions ; any mismatches between the number of slices on a circle and the number of plant names owes to the presence of multiple phases of some plants

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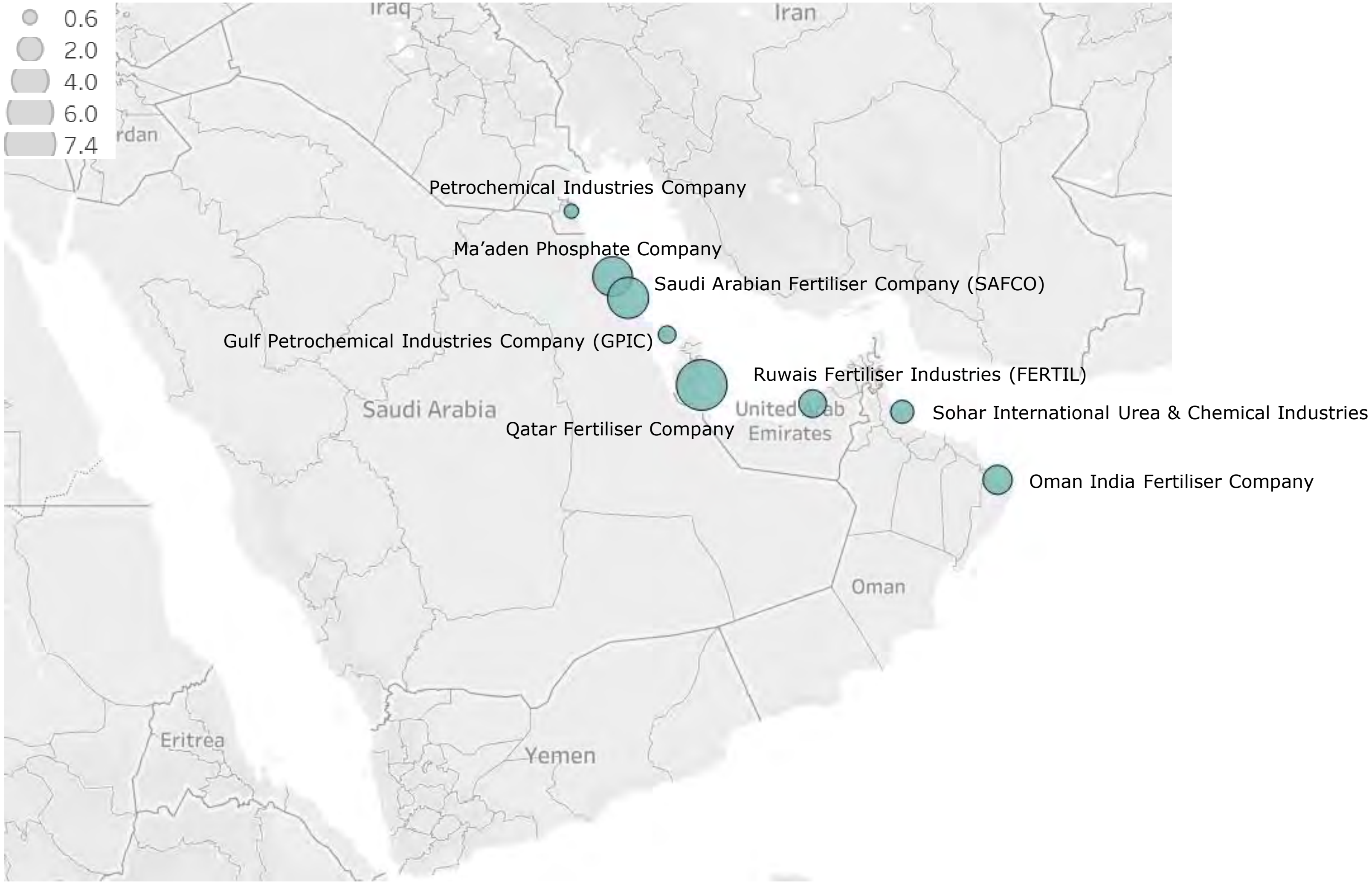
Fertilisers plant location – GCC*



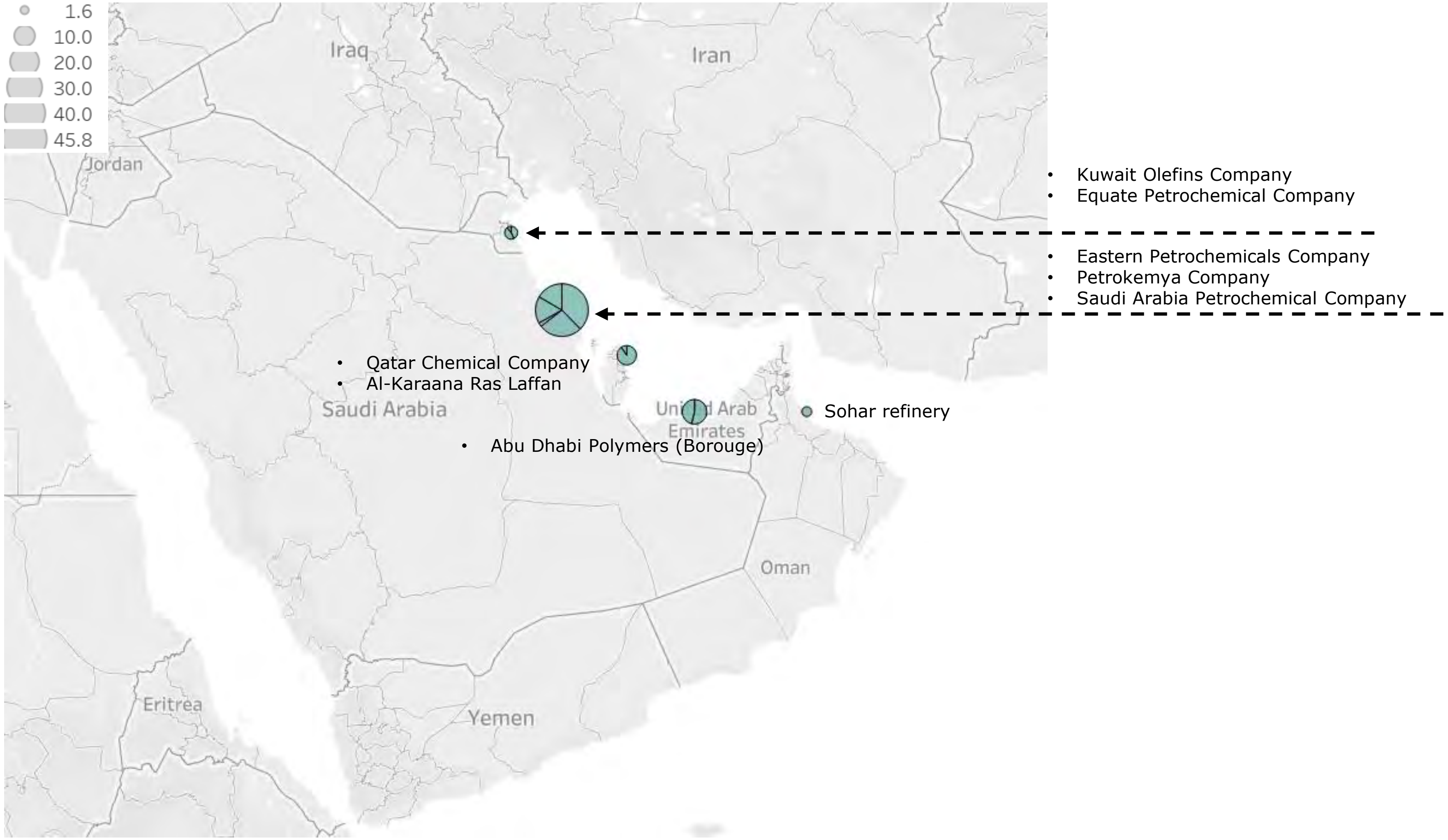
*Circle sizes are proportionate to CO_2 emissions ; any mismatches between the number of slices on a circle and the number of plant names owes to the presence of multiple phases of some plants

Methanol plant location – GCC*

- Arrazi Saudi Methanol Company
- Ibn Sina
- International Methanol Company
- Methanol Chemical Company

*Circle sizes are proportionate to CO_2 emissions ; any mismatches between the number of slices on a circle and the number of plant names owes to the presence of multiple phases of some plants

Petrochemical plants location – GCC*



*Circle sizes are proportionate to CO_2 emissions ; any mismatches between the number of slices on a circle and the number of plant names owes to the presence of multiple phases of some plants

Chapter 3 Tech annex

CCS in Depleted Gas Reservoirs – Estimating Capacity with Material Balance

In its simplest form, the quantity of storable CO_2 in a depleted gas reservoir can be estimated using the following material balance equation (S.K.F. Hattingh, unpublished):

$$CO2Mi = \frac{Gp}{Ei} * \rho CO2i \qquad \text{(Equation 1)}$$

Parameter	Unit	Description
$CO2Mi$	metric tonnes	The mass of CO_2 that can be stored if the depleted gas reservoir is returned to its original pressure
Gp	m^3	The volume of HC gas that has been or will be produced during the depletion phase measured at surface temperature and pressure
Ei	Dimensionless	The initial HC gas expansion factor, i.e. the volume of a unit mass of HC gas at surface temperature divided by the volume of the unit mass of gas at the initial reservoir temperature and pressure
$\rho CO2i$	tonnes/m^3	The density of CO_2 at the original, pre-depletion pressure of the reservoir

Storage sites are usually sought at depths greater than ~800 m, where the normal formation pressure exceeds the critical pressure of CO_2 (72.9 atm or 1,071 psia), resulting in CO_2 being stored efficiently in a dense, or highly concentrated phase. CO_2 is usually more compressible than HC gas in formations with normal temperature gradients, meaning that a large surface volume of CO_2 can be stored in the same subsurface pore volume as a smaller volume of HC gas.

Equation 1 takes account of the different expansion factors for hydrocarbon gas and CO_2. However, the data needed to estimate the HC gas expansion factor (Ei) are not available for this work, and therefore an adaption of Equation 1 has been used, described on the next slide.

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CCS in Depleted Gas Reservoirs – Estimating Capacity with Material Balance

For this study, the primary dataset comprises estimates of past and future recovered and recoverable hydrocarbon gas. Therefore, Equation 1 has been modified to (S.K.F. Hattingh, unpublished):

$$CO2Mi = Gp * Eratio * \rho CO2STP \qquad \text{(Equation 2)}$$

Parameter	Unit	Description
$CO2Mi$	metric tonnes	The mass of CO_2 that can be stored if the depleted gas reservoir is returned to its original pressure
Gp	m^3	The volume of HC gas that has been or will be produced during the depletion phase measured at surface temperature and pressure
$Eratio$	Dimensionless	The ratio of CO_2 to HC gas that can be stored in a fixed pore volume at the initial reservoir temperature and pressure
$\rho CO2STP$	0.00187 tonnes/m^3	The density of CO_2 at standard temperature (60 degF) and pressure (14.7 psia)

The value of $Eratio$ is not constant and depends on temperature, pressure and the composition of the HC gas (all of which are accounted for implicitly in Equation 1).

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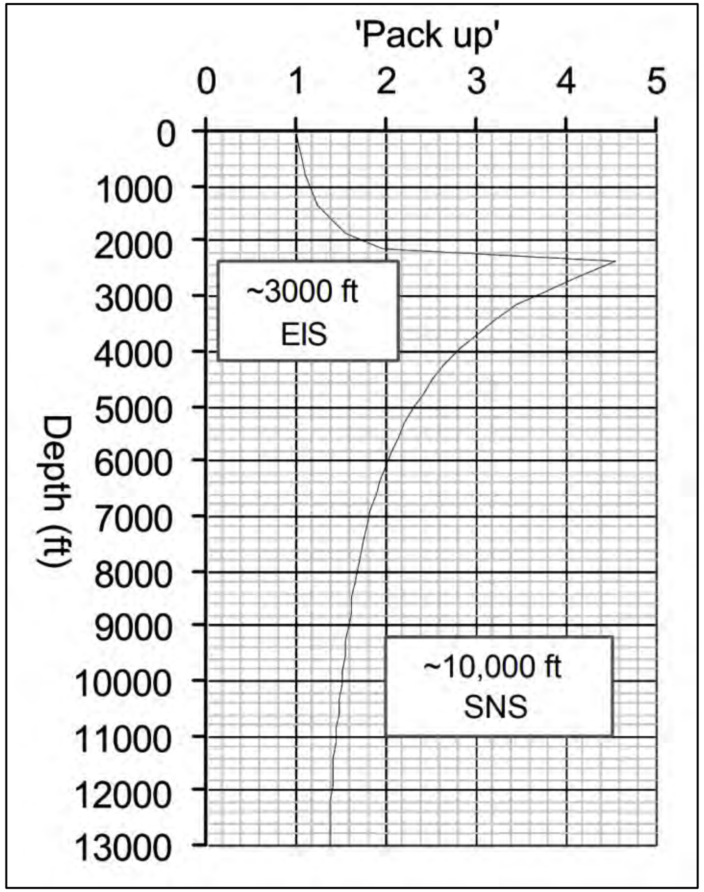
CCS in Depleted Gas Reservoirs – Estimating Capacity with Material Balance

RATIO OF CO_2 TO METHANE EXPANSION FACTORS



Source: Hughes, D.S 2009

DESCRIPTION

- The diagram on the left is an illustration of an example of the ratio of CO_2 to HC gas (in this case methane) expansion factors, annotated as "Pack up" (Hughes, 2009), equivalent to $Eratio$ in Equation 2.
- Based on various studies of real HC gases in specific storage projects, the value of $Eratio$ is expected to vary between about 1.2 and 1.6.
- In making its estimates of theoretical storable volumes of CO_2, GaffneyCline has assumed Low case, Best estimate case and High case values of 1.2, 1.4 and 1.6 for $Eratio$ in Equation 2.

References and Nomenclature

References

– Hughes, D.S., 2009. Carbon storage in depleted gas fields: Key challenges. Energy Procedia 1, pp3009-3014.

Nomenclature

atm	atmospheric pressure
degF	temperature in degrees Fahrenheit
ft	feet
Gt	Giga (10^9) tonnes
m	metres
m^3	cubic metres
psia	pounds per square inch measurement of absolute pressure
tonnes or t	metric tonnes
Tscf	trillions (10^{12}) cubic feet of gas measured at standard conditions

CCS in Depleted Gas Reservoirs – Estimating Capacity Stepwise Approach

Estimates of ultimate recovery of non-associated gas at country level were converted to theoretical estimates of storable volumes using Equation 2. In practice, the theoretical storable quantities are unlikely to be reached for the following reasons:

1) Not all depleted reservoirs are suitable for CCS (suitability factor).

2) Not all suitable reservoirs can be filled to the theoretical maximum (efficiency factor).

CCS in Depleted Gas Reservoirs – Estimating Capacity Stepwise Approach

Detailed field information is needed to evaluate the suitability of individual reservoirs, which is beyond the scope of this work. Based on experience in the region, GaffneyCline has assumed Low case, Best estimate case and High case blanket suitability factors of **30%, 50% and 70%** (suitability factor), applied to the volumetric estimates at country level. **Suitability of depleted gas reservoirs for CCS depends on the following factors:**

Depth

Reservoirs with final storage pressures less than ~1,071 psia do not provide efficient use of the pore volume because CO_2 is in the low-density gas phase below this critical pressure. Conversely, reservoirs at great depth are less attractive because, although the pressure increases with depth and tends to cause the CO_2 density to increase (a desirable effect for efficient storage), temperature also increases with depth and in normal temperature environments this more or less counters the effect of pressure on CO_2 density, so there is little benefit to storing CO_2 at great depth. Additionally, reservoir properties often decrease with depth, which may reduce injectivity and lead to more injection wells, and drilling costs also increase with depth. Some published ranking criteria cite a depth range of ~850 to 2,500 m as suitable.

Injectivity

High permeability and/or thick formations that allow high injection rates are suitable for storage in depleted gas reservoir as this reduces the well count, improves the chances of even fill and lowers the pressure differential between the bottomhole injection pressure and reservoir pressure. Some published ranking criteria imply a suitable permeability-thickness product above 4,000 mDm.

Reservoir complexity

Highly heterogenous formations are potentially unsuitable because of risk of channeling of CO_2 beyond structure and uneven fill.

Containment

Although gas reservoirs have demonstrated containment and seal integrity, conversion to CCS my be unsuitable because of integrity risk of legacy wells. This is particularly important in multiple stacked reservoirs where large numbers of wells penetrate shallower reservoirs.

Source–sink pairing

Source-sink pairing in terms of capacity, timing and location and can lead to candidates being screened out

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CCS in Depleted Gas Reservoirs – Estimating Capacity Stepwise Approach

Filling of depleted gas reservoir for CCS

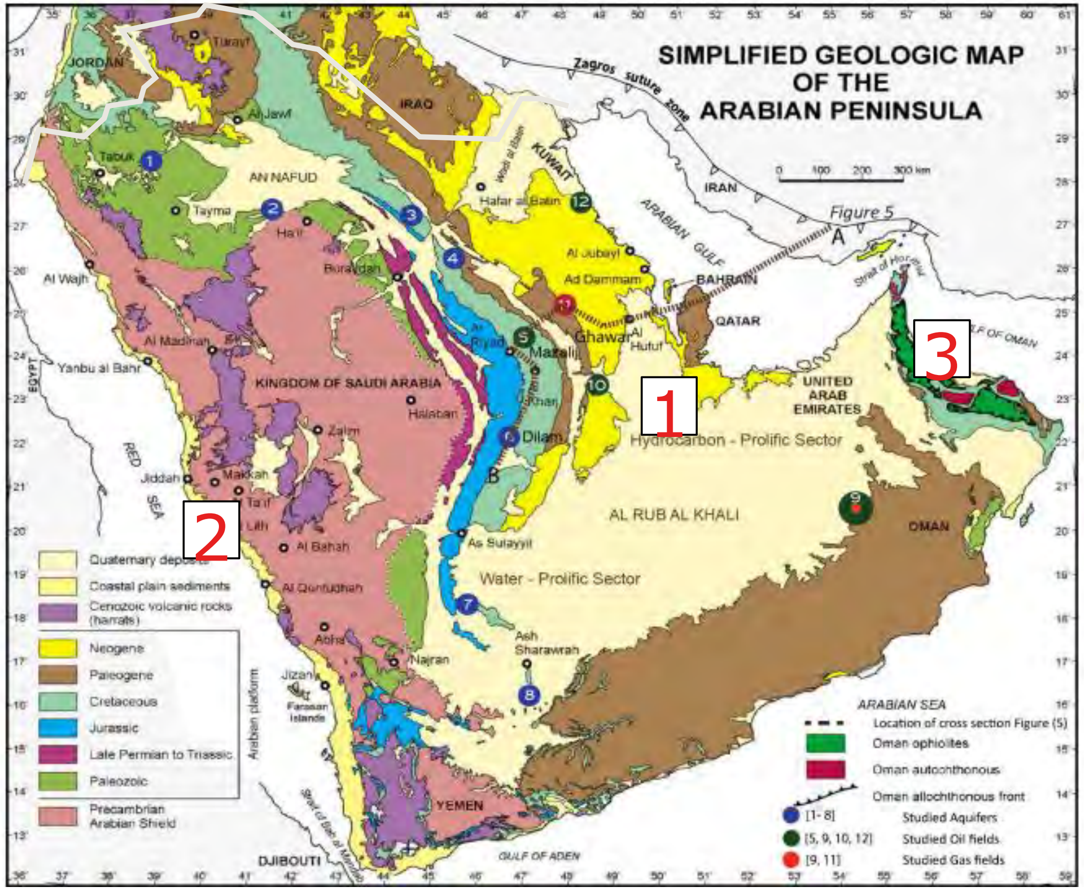
The material balance Equation (Equation 1) does not take account of the following:

- Loss of storage pore volume due to aquifer influx – can be very large
- Loss of storage pore volume from condensate drop out – can be large in some cases
- Interaction between native HC gas and CO_2 – effect is poorly understood (mixing, banking, segregation, changing Z-factor)
- Cooling effect of injecting CO_2 – potentially store more CO_2 at lower temperature, but CO_2 expands as temperature rises again later, causing latent pressure increase.
- Loss of pore volume due to hysteresis in pore volume compressibility – small
- Heterogeneity leading to poor filling efficiency and loss of storage pore volume - can be large
- Increase in storage due to dissolution of CO_2 in connate water – small
- Increase in storage due to dissolution of CO_2 in water outside poot – can be large
- Loss of CO_2 storable volumes due to impurities in injectant;
- Potential corrosion effects on well tubulars, jewelry and wellheads etc.

Each of these points requires analysis at specific field level. Based on the literature and on experience, GaffneyCline has assumed Low case, Best estimate case and High case blanket efficiency factors of **75%, 85% and 100%**.

Study Area & Definitions

INVESTIGATED SINKS



Source: Geological map from Jaju et al. (2016)

DESCRIPTION

- This part of the project addresses investigation of potential carbon sinks of two types:
  - Saline aquifers. Storage of CO_2 in extensive subsurface water-bearing porous units.
    - (1) Rub'al-Khali Basin: Large, long-lived sedimentary basin on the northeastern flank of the Arabian Platform, in part forming the foredeep of the Zagros and Oman Mountains
    - (2) Red Sea Basins: Extensional, fault-controlled basins on the margins of the incipient ocean of the Red Sea
  - "Geological storage" sequestration by direct mineral reaction with the rocks that comprise the (3) Oman ophiolite. Obducted oceanic crust on the Oman continental margin

Saline aquifers: Methods

- Identification of principal aquifer/reservoir systems and bounding sealing units
- Characterisation in terms of:
  - Injectivity
  - Storage capacity
  - Containment risks
- Key controlling factors, with mapping of boundaries and cutoffs
- Summary map presentation
- Data table summary
- Provisional estimates of storage capacity

Assessment criteria

- The following slides list the component criteria that impact the three main aspects of CO_2 storage plays:
  - Injectivity –Can the target reservoir receive CO_2 at the rate required by the commercial or other needs of the scheme? Fundamentally, this depends on the permeability and reactivity to CO_2 of the injection zone.
  - Storage – Overall can the reservoir achieve the long term storage requirements, taking into account all of the habits of CO_2 in the subsurface? It critically depends on porosity and the reservoir heterogeneity
  - Containment – Are the risks associated with long term viability of the sealing mechanisms acceptable? This is mostly associated with the integrity of the sealing horizons, both top and lateral, and the propensity of the area for faulting and fracturing.
- The following slides are presented in the form of a check list for each component, with comments on likely cut-offs that have been applied in previous work, either from the literature or developed by GaffneyCline.

Injectivity checklist

Factor	Positive	Negative	Rationale and commentary
Depth - Minimum	>1000m	<800m	Need for CO_2 to be present as a supercritical fluid phase. Minimum Critical Pressure is 73.8 bar
Depth - Maximum	<2500m	>2500m	Likely declines in permeability and higher injection pressure required
Permeability	>300mD	<200mD	Some sources quote ideal 1000mD, others as low as 20mD, but with average in 100s mD. Low permeability may increase the importance of fractures.
Lithology	Sandstone (quartzose)	Carbonate and arkosic sandstone	Re-precipitation in carbonates that may occlude porosity and more complex pore systems.
Residual gas/condensate/oil saturation	Low	High	Affects relative permeability to CO_2 and injectivity
Gas composition	Pure CO_2	Impure CO_2	Critical pressure may increase with impurity, and introduce a two-phase region. Also possibility of hydrates, in presence of water.

Storage checklist

Factor	Positive	Negative	Rationale and commentary
Overall geometry of system	High impedance, Laterally Drained	Low impedance, Vertically Drained	Requirement is to promote extensive lateral spread of CO_2 plume, contained by seals, without leakage
Porosity	>20%	<10%	Adequate CO_2 storage
Heterogeneity	Moderate heterogeneity but no with major barriers and baffles	Homogeneous or strongly compartmentalised reservoir	Promotes higher residual CO_2 saturation and storage efficiency
Open or closed?	Well defined system/open	Poorly defined system/closed	Determines confidence in likely response to pressure and storage efficiency
Reservoir thickness	>50m	<20m	Adequate CO_2 storage
Trap geometry	Well defined	Poorly defined	Depleted field and trapping geometries within saline aquifer unit

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Containment checklist

Factor	Positive	Negative	Rationale and commentary
Seal thickness	>100m	<20m	Thicker seal more likely to be regionally continuous. Fault juxtaposition and fault plane sealing favoured.
Depth of seal	>1000m	<800m	Phase change of fluid and change of density
Lithology	Mudstone with organic-rich units and/or carbonates	Mudstone with siltstone or sandstone	Seal capillary entry pressure and/or adsorption
Fracturing	Absent	Present	Local areas with low capillary entry pressure,
Faulting	Absent	Present	May require understanding of stress regime to determine likely fault activity
Seismicity	Low	Moderate to High	
Well density	Low	High	Well penetration points and potential corrosion.
Relationship with aquifer	Simple	Complex	No local hydrodynamic effects or compaction flow

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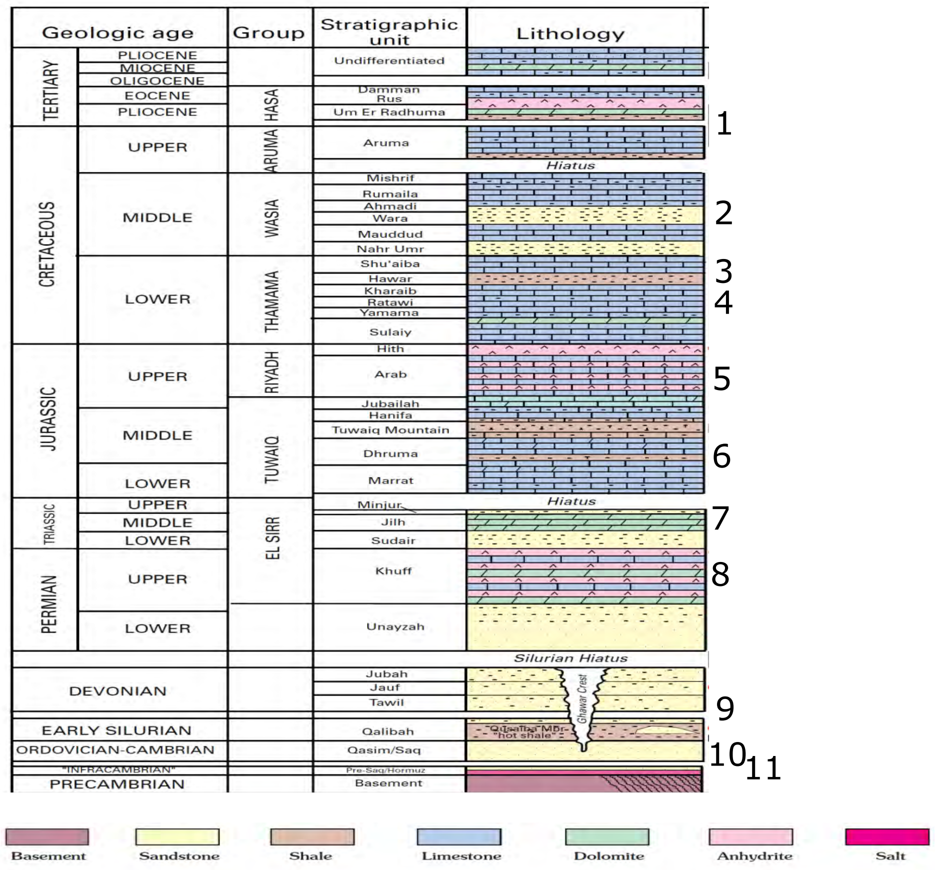
General stratigraphic column

GENERAL STRATIGRAPHIC COLUMN



Source: Vahrenkamp et al., 2021

DESCRIPTION

- Overall setting is widespread, long-lived passive margin platform, with extensive reservoir and seal units.
- Principal reservoir/aquifer zones recognised here are numbered (see following slide)
- Each is identified by a prominent reservoir and seal
- They may be the basis of a recognised petroleum play, or recognised potable aquifer system

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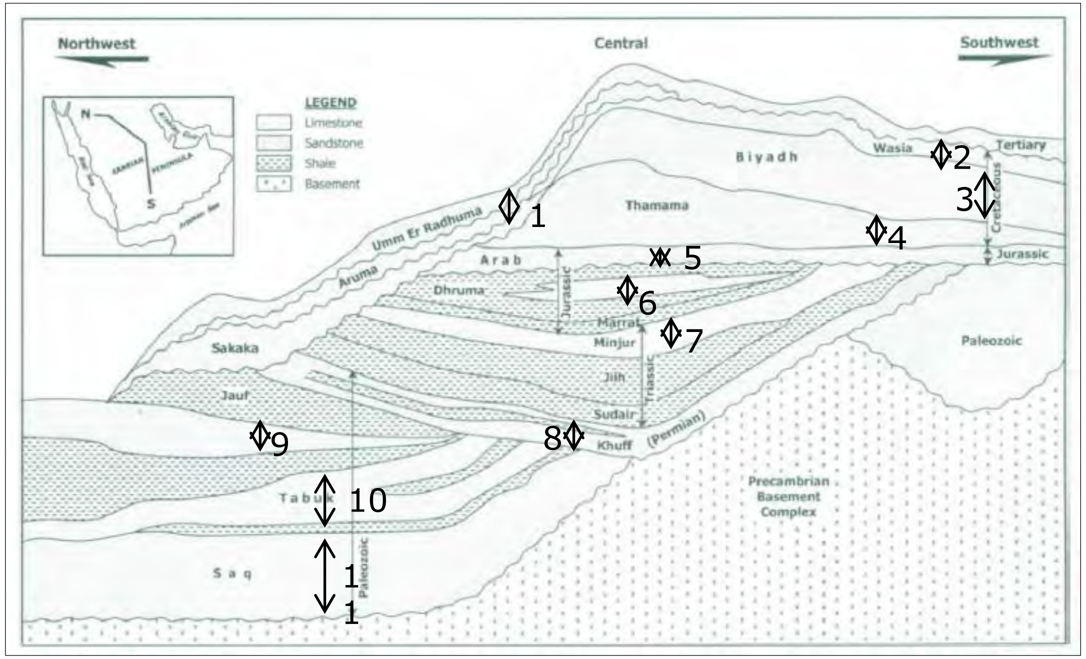
Rub'al-Khali Basin: Reservoir units

Unit (this study)	Age	Principal reservoir unit	Secondary reservoir	Principal seal	Corresponding aquifer system (Jaju, 2016)
1. Umm er Radhuma/Aruma	Late Cretaceous - Paleocene	Umm er Radhuma	Aruma Group	Rus	UER and Aruma aquifers
2. Wasia	Late Cretaceous	Mishrif, Ruwaydha, Natih, Burgan Sandstone		Laffan	Khurais Super-aquifer
3. Shuaiba	Early Cretaceous	Shuaiba		Bab	Buwaib Meso-aquitard
4. Thamama	Early Cretaceous	Kharaib, Zubair Sandstone	Lekhwair, Habshan	Hawar	
5. Arab	Late Jurassic	Arab		Hith	Layla Aquifer
6. Araej	Middle Jurassic	Tuwaiq Mountain, Araej	Dhruma	Hanifa	Az Zulfi Aquifer
7. Minjur	Late Triassic	Lower Minjur	Jilh, Gulailah	Upper Minjur	Kharj Super-aquifer
8. Khuff	Permian	Khuff, Unayzah, Al Khlata		Sudair	Raffah Super-aquifer
9. Tawil	Early Devonian	Tawil	Jauf	Middle Jauf	Jalamid Super-aquifer
10. Tayma	Late Ordovician	Sarah, Quwarah	Kahfah	Qusaiba	Hail Super-aquifer
11. Saq	Middle Cambrian – Early Ordovician	Saq		Hanadir	Saq Super-aquifer

Overview of reservoir and aquifer systems

NW-SE SECTION ACROSS RUB'AL-KHALI



DESCRIPTION

- Approximately NW-SE section across the Rub'al-Khali Basin, showing the relationship between the reservoir systems examined here and the aquifer systems recognised by Alsharhan et al., 2016.
- Numbering system as in previous slides

Source: After Alsharhan et al., 2001

Sequence 1: Umm er Radhuma: Data summary

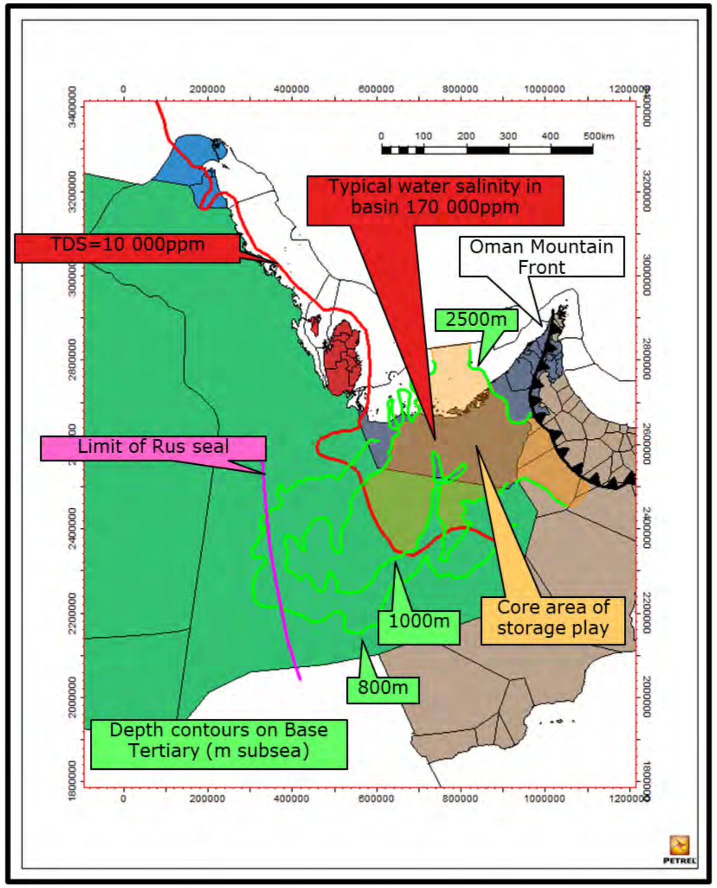
Description	
Umm er Radhuma limestones (Paleocene to Lower Eocene) occur in the axis of the Rub’al-Khali Basin. Critical to the storage play is the overlying extensive Rus evaporite seal (Eocene). Supplementary seals may be present to the east of the Qatar Arch on the underlying Simsima and Aruma Group that extend the play stratigraphically downwards.	
Injectivity	
Permeability	Limited data suggest moderate 10-100mD range.
Lithology	Limestone, locally dolomitic. Cherts near base.
Storage capacity	
Indicative depth	Map shows the key 800m, 1000m, and 2500m subsea contours. Typical depths are in the range 1500-2500m.
Porosity	No detailed information but porosities of 15-20% expected based on regional data. Key risk would be presence of tight micritic or argillaceous limestones.
Reservoir type	Shallow marine carbonate platform. Laterally extensive facies.
Containment	
Top and lateral sealing	confidence in Rus top seal anhydrite expected to be widespread. Additional mudstone seal at top Aruma Group
Overall rating	Moderate

Sequence 1: Umm er Radhuma

COMMENTARY

- Shallow play in part in key 1000-2500m burial zone
- Limit of Rus seal not a critical controlling factor
- No lithological controls recognised
- Widespread potable aquifer, so minimum salinity recognised as key control
- Storage play fairway in centre of Rub'al-Khali Basin in UAE, Saudi Arabia and Oman

STORAGE PLAY FAIRWAY MAP



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Sequence 2: Wasia: Data summary

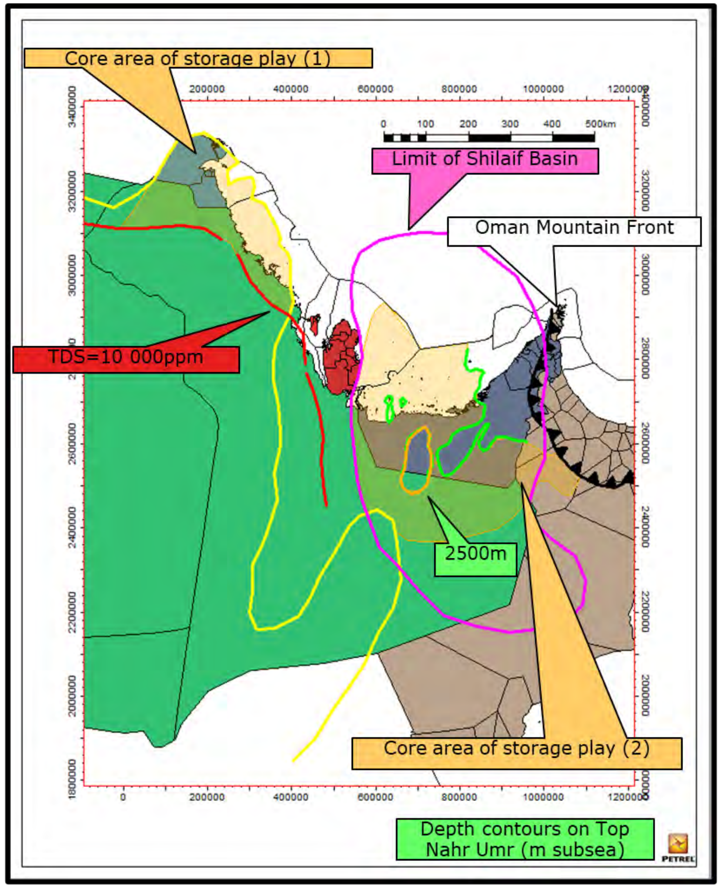
Description	
There are two areas of interest: the northern Gulf area comprises the Burgan and Wara Sandstones, representing deltas sourced into the northwestern part of the basin, and the southern Gulf area comprises the equivalent Mishrif open marine carbonates. The reservoir units are Albian to Turonian (Cretaceous) age.	
Injectivity	
Permeability	Best quality in sandstones 100-1600mD, optimum in fluvial channels, average 270-mD in marine/tidal sands. Moderate quality in limestones 50-100mD, optimum in shoal/biostrome facies.
Lithology	Limestone (Mishrif and Ruwaydha), Sandstone (Burgan and Wara).
Storage capacity	
Indicative depth	Area of interest 1500 to 2500 m.
Porosity	Sandstones 20-25%. Limestones up to 20%.
Reservoir type	Sandstones deltaic to shallow marine. Limestones are platform carbonates with localised rudist build-ups at platform margins. These are expected to be associated with enhanced reservoir quality.
Containment	
Top and lateral sealing	Top seal on the Burgan sands is provided by the Ahmadi Shale. For the Mishrif and Ruwaydha the ultimate top seal is the Laffan shale, but with significant and multiple Shilaif Formation intraformational seals. Note that these comprise organic-rich and argillaceous limestones.
Overall rating	Good

Sequence 2: Wasia

COMMENTARY

- Two areas of potential recognised.
- Burgan sandstone. Storage play fairway in Kuwait and Northern Saudi Arabia
  - Generally between 1000-2500m subsea
  - Lithological limit of Burgan deltaic sandstones defines limit to northeast
  - Potable aquifer recognised to southwest provides limit of storage play fairway
- Mishrif and Ruwaydha and equivalents Storage play fairway in centre of Rub'al-Khali Basin in Qatar, UAE, Saudi Arabia and Oman
  - 2500m depth used to delineate play fairway
  - Outline of Shilaif Basin used to delineate play fairway as this defines area containing shelf-edge build-ups and also best developed intraformational seals (Shilaif and Tuwayil Formations.)
  - The storage play fairway is extended eastwards into the area of the equivalent Natih Formation petroleum play in Oman

STORAGE PLAY FAIRWAY MAP



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Sequence 3: Shuaiba: Data summary

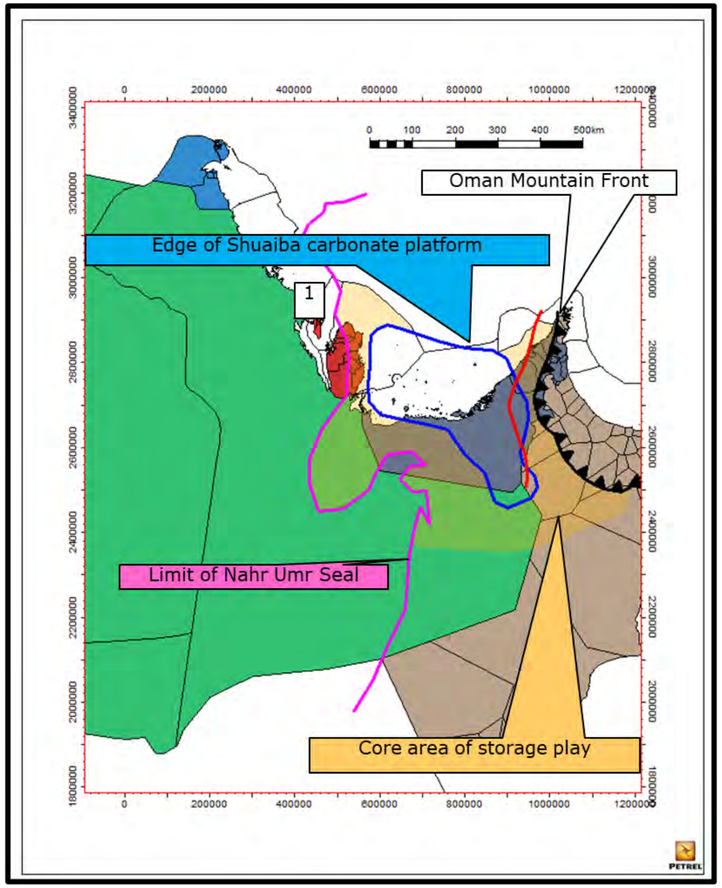
Description	
The Shuaiba Formation (Aptian, Lower Cretaceous) forms an attractive storage play in areas where optimum carbonate platform reservoir coincides with the overlying seal of the Bab Member, in the equivalent basinal facies, orsealing by the overlying Nahr Umr mudstones.	
Injectivity	
Permeability	Poor-moderate 10-200mD with optimum reservoir quality in shelf edge build-ups where average permeability is expected to exceed 100mD and is rated moderate.
Lithology	Limestone.
Storage capacity	
Indicative depth	2250 – 2750m
Porosity	18—25%, with a porosity floor suggested by regional data of approximately 3000m
Reservoir type	Shelf edge build-ups with optimum reservoir quality on the fringes of the carbonate platform, with additional reservoir quality in the platform interior.
Containment	
Top and lateral sealing	Mudstones and argillaceous limestones of the Bab Member and Nahr Umr Formation.
Overall rating	Good

Sequence 3: Shuaiba

COMMENTARY

- Moderately deep play over 2500m burial zone. Included because of excellent reservoir quality in Shuaiba build-ups despite depth.
- Controlled by limit of well-developed Nahr Umr mudstone seal
- Key zone surrounds Bab Basin, where optimum Shuaiba facies is expected
- The storage play fairway is extended eastward into the area of the equivalent petroleum play in Oman.
- No potable aquifer recognised, so minimum salinity not recognised as key control, although Note 1. Waters of 6500 ppm (NaCl) recognised at Awali Field, Bahrain.
- Storage play fairway in centre and eastern margin of Rub'al-Khali Basin in Qatar, UAE, Saudi Arabia and Oman

STORAGE PLAY FAIRWAY MAP



Sequence 4: Thamama: Data summary

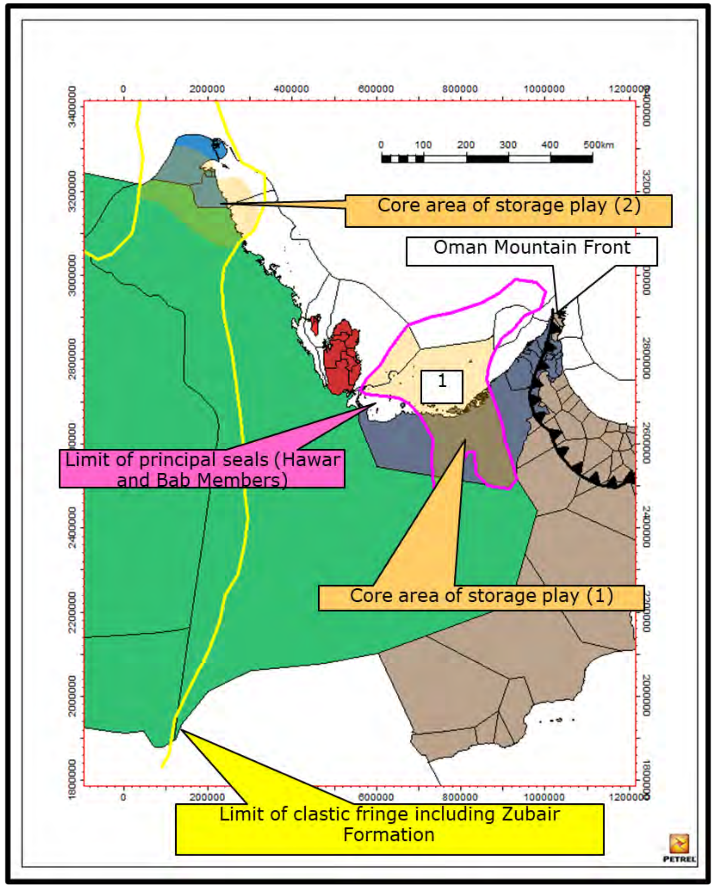
Description	
As with the Wasia Group, there are two areas with Lower Cretaceous reservoir potential. A marine carbonate storage play in the southern Gulf in the Thamama Formation, and an equivalent deltaic sandstone storage play in the northern Gulf, in the Zubair Formation.	
Injectivity	
Permeability	Moderate quality, approximately 50mD for limestones. Sandstones good quality 150-550mD
Lithology	Limestone (Thamama Group). Sandstone (Zubair Formation)
Storage capacity	
Indicative depth	1550-1850m in Burgan area, Kuwait, deepening northeastwards. The carbonate play in the southern gulf is deeper at approximately 2500m.
Porosity	15—20%, with a porosity floor suggested by regional data of approximately 3km. Zubair Formation approximately 15-25%.
Reservoir type	Deltaic-shallow marine sandstones. Mapped limit corresponds to approximately 40% NTG, which rapidly declines to the northeast. Mosaic of platform interior facies for the carbonate play, extensive but with some variability.
Containment	
Top and lateral sealing	Hawar Shale and Bab Member argillaceous limestones are seals on top of Thamama Group. Upper Zubair Formation mudstones and Shuaiba tight carbonates act as seal on Zubair Formation, along with intraformational mudstone seals
Overall rating	Moderate-Good

Sequence 4: Thamama

COMMENTARY

- Two areas of potential recognised.
- Zubair sandstone. Storage play fairway in Kuwait and Northern Saudi Arabia
  - Generally between 2500-3000m subsea
  - Lithological limit of Zubair Deltaic sandstones defines limit to northeast
- Thamama Limestone. Storage play in Qatar and UAE.
  - Controlled essentially by limit of well-developed Hawar and Bab Member mudstone seals.
  - No other lithological controls
  - Note 1. Documented water salinity > 75,000ppm TDS in offshore Emirates. No salinity cut-off used to define play.

STORAGE PLAY FAIRWAY MAP



Sequence 5: Arab: Data summary

Description	
Arab reservoirs (Kimmeridgian-Tithonian, Upper Jurassic) comprise the principal oil and gas reservoirs, and are conventionally divided into Zones A-D. The ultimate seal is the Hith evaporite at the top of the Arab A, but here the possibility of multiple intraformational seals is emphasised, especially in the basinal areas recognised as the core of the storage play fairway.	
Injectivity	
Permeability	Complex local diagenesis associated with solution and dolomitisation may greatly enhance permeability to up to good values of approximately 200mD. In general, however, poor to moderate 3mD to 50mD, averaging 10mD.
Lithology	Limestone and dolomite. Overall dolomite comprises 75% of the unit. Some evidence that dolomite is more stable to CO_2 injection.
Storage capacity	
Indicative depth	Approximately 2000m in south of defined areas, but increasing to 3500m in north, offshore. Despite greater depth, this play is included because of locally good potential reservoir injectivity.
Porosity	10-15%, but increasing to 25% in areas with strong solution porosity and dolomitisation. Some data suggest this is preferential in western storage play fairway area compared to eastern.
Reservoir type	Open shelf and ramp carbonates with localised middle and upper ramp grainstones, especially in the Arab D. Intra-shelf lagoonal deposits in Arab A-C.
Containment	
Top and lateral sealing	Ultimate top seal provided by Hith evaporite, but of great significance may be supplementary evaporite cycles between the Arab A-D reservoir units. Top D anhydrite seal is critical in Greater Ghawar area. Faulting associated with prominent structural axes may affect seal relationships.
Overall rating	Moderate-Good

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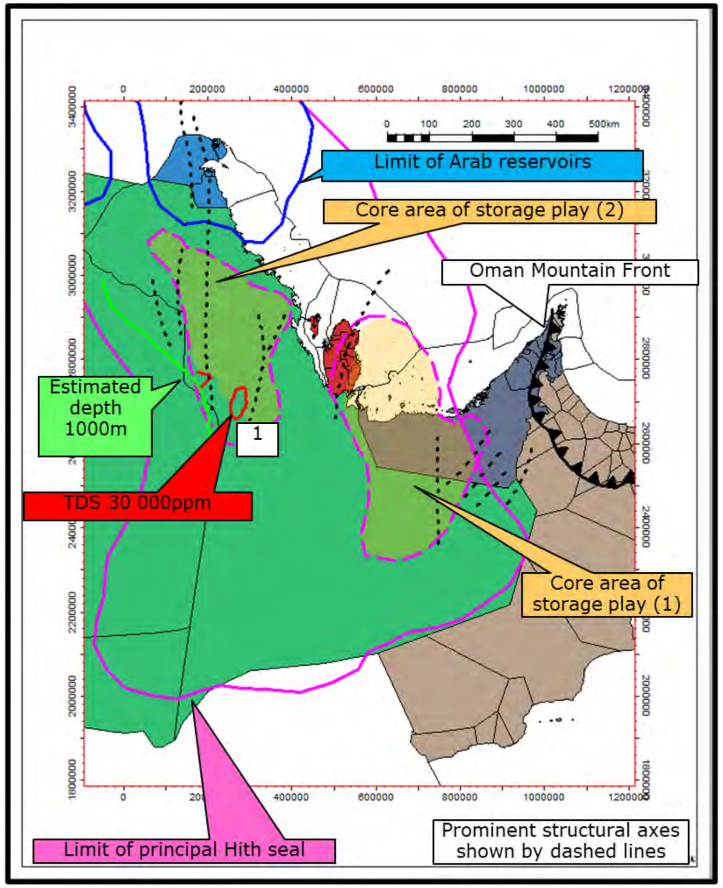
Sequence 5: Arab

COMMENTARY

- Two areas of potential recognised.
- Although Arab reservoirs are widespread, focus is on intrashelf basinal areas, where (i) multiple stacked reservoirs are present, bounded by evaporite seals, and (ii) there is preferential grainstone reservoir development on the margins.
- No other lithological criteria is used.
- The limits of the overlying Hith Formation seal are not a critical factor, except in far east.
- Depths are variable. A play fairway is recognised in the offshore areas because of the possibility of excellent reservoir quality, despite the greater depth (c. 3500m). In the far west, depths approach the critical 1000m limit.
- No salinity cut-off applies, although fresher waters (approximately 30 000ppm TDS are seen in the west (Note 1).

STORAGE PLAY FAIRWAY MAP



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Sequence 6: Araej: Data summary

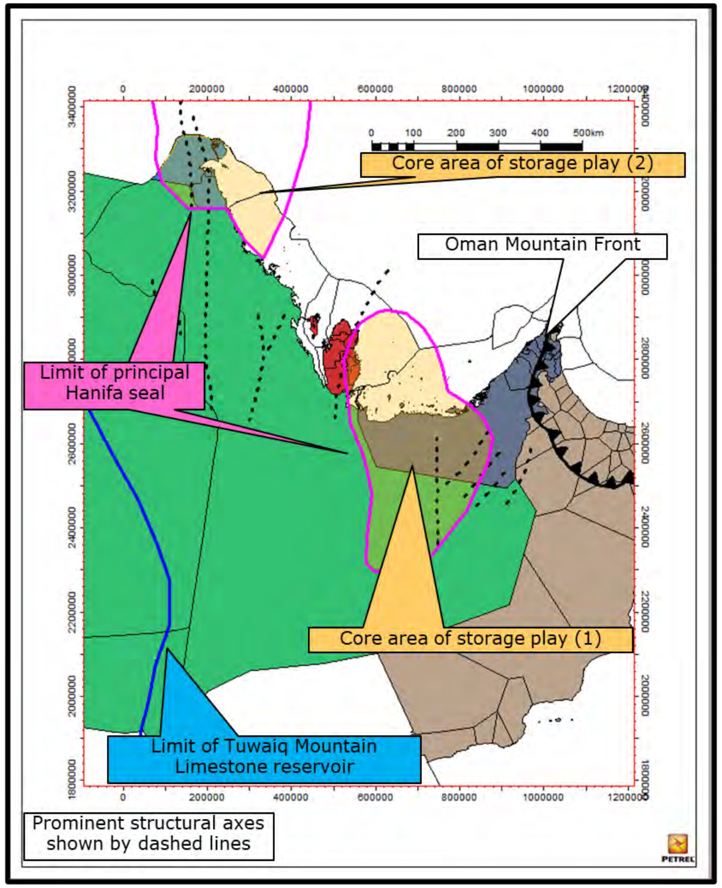
Description	
Lower and Upper Araej and associated Tuwaiq Mountain Limestone reservoirs (Callovian to Oxfordian, Middle to Upper Jurassic) are extensive in the study area, but are relatively deep and tight. Nonetheless a storage play fairway is tentatively identified where they are overlain by Hanifa seals (Upper Jurassic).	
Injectivity	
Permeability	Less than 0.7mD reported, suggests only poor injection performance likely.
Lithology	Limestone, partially dolomitised.
Storage capacity	
Indicative depth	3-3.5km. Unlikely to be attractive except in the vicinity of the Qatar Arch or other structural highs.
Porosity	6-12% suggests that this play be of marginal quality.
Reservoir type	Shallow marine carbonate platform/ramp.
Containment	
Top and lateral sealing	Hanifa and Naokelekan deep marine mudstones and limestones (Upper Jurassic).
Overall rating	Poor

Sequence 6: Araej

COMMENTARY

- Two areas of potential recognised.
- Play is entirely delineated by the presence of the overlying Hanifa organic rich mudstones.
- No other cut-off criteria are applied.
- Depths and reservoir quality likely render this play of marginal interest only.

STORAGE PLAY FAIRWAY MAP



Sequence 7: Minjur: Data summary

Description	
The Minjur sandstone (Upper Triassic) is an important aquifer on the eastern margin of the Arabian Platform, with significant penetration of fresh water. Its potential as a CO_2 storage site is limited to areas away from this freshwater influx. Along with other key controls, depth is likely to limit the potential to a very small part of the basin.	
Injectivity	
Permeability	No detailed data recorded. General porosity-permeability relationships suggest moderate 50-200mD.
Lithology	Sandstone
Storage capacity	
Indicative depth	Mostly greater than 3.5km. Area of potential likely to be limited to western part of basin, or to flanks of structural highs.
Porosity	Porosity of 17% assumed in previous study of aquifer potential, although subsurface porosities estimated to be 12% based on porosity-depth information.
Reservoir type	Alluvial to fluvial sandstones, with variability of sedimentary facies depending on channel distribution.
Containment	
Top and lateral sealing	Upper Minjur mudstones (Upper Triassic), along with various overlying units in the Lower Jurassic.
Overall rating	Poor-Moderate

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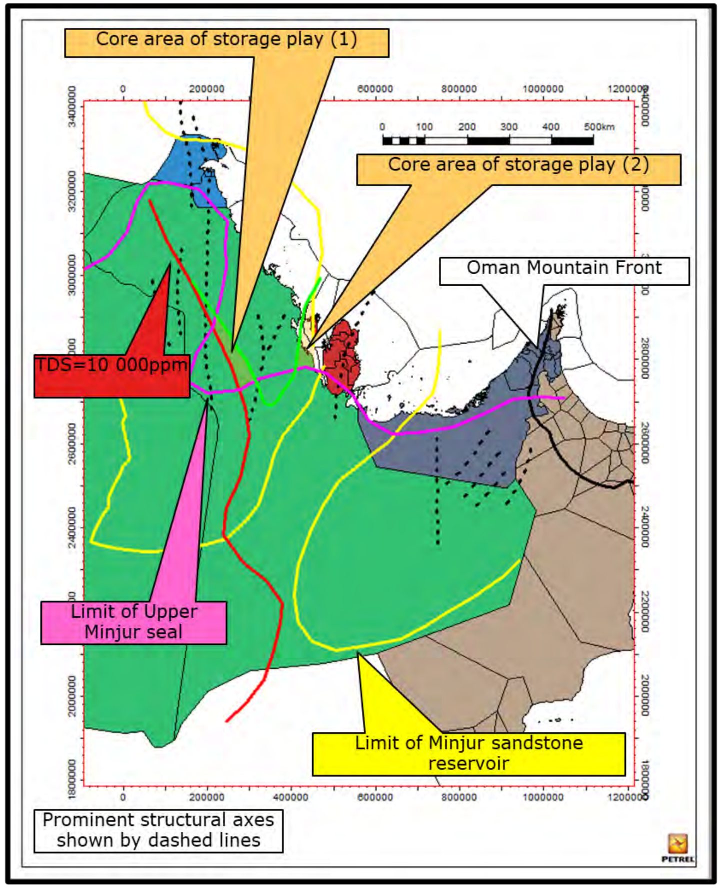
Sequence 7: Minjur

COMMENTARY

- Three areas of potential recognised.
- The reservoir is expected to be absent over the Qatar Arch, separating western and eastern areas.
- Two in the west are limited by the depth of the reservoir and the estimated limit of the potable aquifer.
- The estimated limit of sealing horizons in the Upper Minjur limit the storage play fairway in the east.
- Storage play fairways thus principally exist in Saudi Arabia and UAE.

STORAGE PLAY FAIRWAY MAP



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Sequence 8: Khuff: Data summary

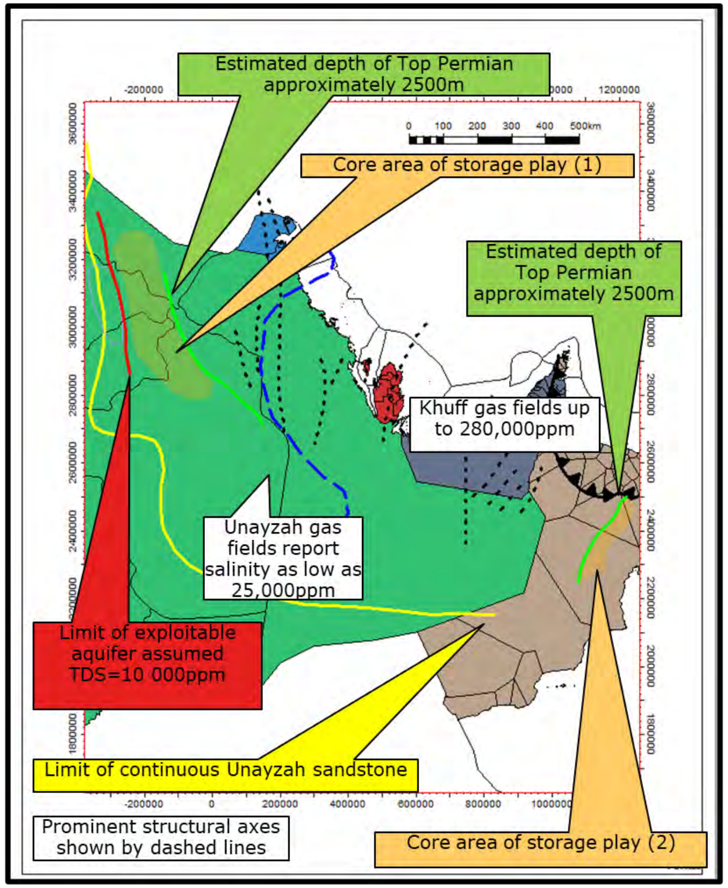
Description	
The Khuff (Upper Permian) and related Unayzah Formation (Lower Permian) are gas reservoirs in the deep part of the Rub'al-Khali Basin, but are generally tight. A poor quality Khuff aquifer is identified in the north west. It is conceivable that a storage play exists downdip of this, but is probably limited by poor reservoir quality. Elsewhere the Khuff is interpreted as at too great a depth (over 5km in Kuwait). The underlying Unayzah equivalent (Lower Permian, Haushi Formation) is potentially important in Oman.	
Injectivity	
Permeability	Poor. 10-20mD, exceptionally up to 100mD, in Khuff dolomites. Moderate to good, over 100mD expected in Haushi sandstones.
Lithology	Limestone and dolomite (Khuff Formation). Sandstone (Unayzah and Haushi Formations).
Storage capacity	
Indicative depth	In both cases the fairway is in the shallow part of the basin, constrained downdip by estimated depths of 2500m.
Porosity	Low porosities are recorded in the aquifer(3-5%), but porosity-depth trends suggest up to 12% at shallow depths in more favourable reservoir facies to the east. Unayzah sandstones range from 5-25% in the Ghawar area. Haushi sandstones are up to 20%.
Reservoir type	Extensive dolomitised platform carbonates, with local grainstone build-ups. Reservoir quality in the target area is the main uncertainty. Contribution from Unayzah and Haushi Formations glacio-lacustrine and fluvial sandstones. Both reservoir facies expected to be extensive.
Containment	
Top and lateral sealing	Top seal is provided by the Sudair Formation mudstones (Lower Triassic), but with additional anhydrite intraformational seals. The Rahab Formation (Lower Permian) top seal is important for the Haushi Formation. In the latter case, intraformational mudstones are not interpreted as significant seals.
Overall rating	Poor-Moderate

Sequence 8: Khuff

COMMENTARY

- Storage play fairways are recognised, downdip of the Khuff potable aquifer, in Saudi Arabia, and associated with the Unayzah equivalent (Al Khlata) petroleum play in Oman.
- Relatively poor reservoir quality limits the Khuff play downdip, so the storage play fairway is cut off by an estimated depth contour.
- The Al Khlata storage play fairway is also delineated by estimated critical depth contours of approximately 1000 and 2500m, along with the reservoir limit in the south of the basin.
- Salinity data from the Khuff and Unayzah gas fields suggest moderate to very high salinities are widespread.

STORAGE PLAY FAIRWAY MAP



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Sequence 9: Tawil: Data summary

Description	
Tawil Sandstones (sensu Sharland et al., 2001) (Lower Devonian) underlie the shales of the Jauf Formation (Lower Devonian) to create this storage play, although the latter unit consists also of sandstones elsewhere. It is referred to as the Upper Tabuk aquifer system by Alsharhan et al., 2001, and part of the Upper Wajid by UN-ESCWA & BGR, 2013.	
Injectivity	
Permeability	No data recorded. Based on regional porosity-permeability correlations moderate to good, over 100mD expected.
Lithology	Sandstone, reportedly variable in composition.
Storage capacity	
Indicative depth	-
Porosity	10-20% in Tawil sandstone. Lower porosities in the underlying Sharawra Formation.
Reservoir type	Fluvial sandstones, with variability of sedimentary facies depending on channel distribution.
Containment	
Top and lateral sealing	Jauf Formation mudstones, also unconformably overlain by Sudair (Lower Triassic) in places
Overall rating	Moderate-Good

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Sequence 10: Tayma: Data summary

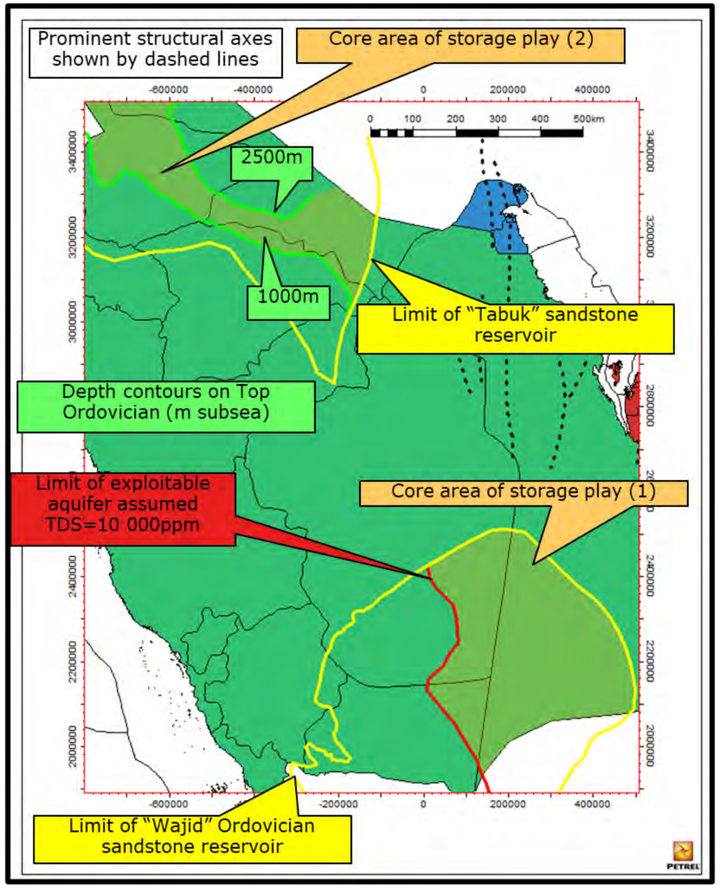
Description	
The system here refered to as Tayma is equivalent to aquifer system referred to as Lower Tabuk (Alsharhan et al., 2001) or Lower Wajid (UN-ESCWA & BGR, 2013). It is Upper to Lower Silurian in age. An area of exploitable aquifer is defined in the far south of Saudi Arabia, with a tentatively defined downdip area. There is little data to characterize this. It may also be a minor contributor in the northwest of the country, above the Saq aquifer (q.v.)	
Injectivity	
Permeability	No data but permeabilities expected to be moderate to good, 50md to over 100mD
Lithology	Sandstone, reportedly variable in composition.
Storage capacity	
Indicative depth	Mapped window of 1000-2500m in north, not well defined in south, but estimated to be in same approximate range.
Porosity	8-20% in Tabuk sandstone in northwestern Saudi Arabia
Reservoir type	Extensive fluvio-glacial sandstones.
Containment	
Top and lateral sealing	Qusaiba Formation (Lower Silurian) organic-rich mudstone at top is regionally extensive with the Ra’an Member mudstone (Upper Ordovician) providing an important additional intraformational seal.
Overall rating	Moderate-Good

Sequence 9 & 10 Tawil & Tayma

COMMENTARY

- This map presents generalised information for the Tawil and Tayma storage plays.
- Potential is restricted to Saudi Arabia.
- In the north both plays are present and recognised as an extension of the middle and upper “Tabuk” aquifers. Depth contours on the Top Ordovician are used to bracket the play, along with an estimated southeasterly limit of the reservoir.
- Only the lower, Tayma play is inferred as present in the south, limited by the extent of the reservoir, and by exploitable fresh water aquifers to the southwest.

STORAGE PLAY FAIRWAY MAP



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Sequence 11: Saq: Data summary

Description	
The Saq Formation is a long ranging (Middle Cambrian to Lower Ordovician) unit on the northwestern margin of the Rub'al-Khali Basin, which is an important aquifer. Storage potential is recognised downdip.	
Injectivity	
Permeability	No data. Expected to be moderate to good, over 100mD.
Lithology	Sandstone, reportedly quartzose, and therefore likely unreactive to CO_2 injection.
Storage capacity	
Indicative depth	The sandstone is extensive. The area estimated between approximately 1000-2500m is used to define the storage play fairway.
Porosity	Reported to be 10-20% in aquifer, but likely to be lower porosity further downdip.
Reservoir type	Extensive fluvial-alluvial sandstones.
Containment	
Top and lateral sealing	Hanadir Shale (Middle Ordovician) is well-developed in north-western Saudi Arabia and provides the principal seal.
Overall rating	Good

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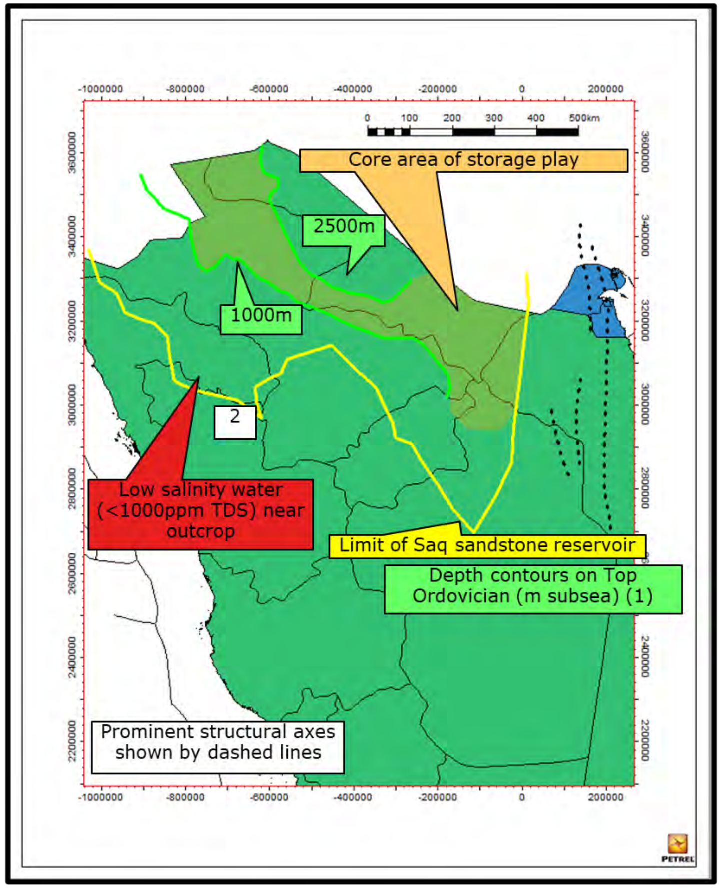
Sequence 11: Saq

COMMENTARY

- The Saq storage play exists in northern Saudi Arabia, downdip of the exploitable potable aquifer.
- The storage play fairway is limited by the approximate extent of the reservoir sand and by approximate depth contours.
- Note (1) that depth contours do not correspond exactly to mapped sequence, but provide a general guide to the depth corridor.
- Note 2. Approximate outcrop position on western margin

STORAGE PLAY FAIRWAY MAP



Rub'al-Khali Basin: Quantitative estimates of storage potential: Inputs

- Inputs:
  - Storage play area – from mapping of key cutoffs
  - Reservoir thickness – from overall stratigraphic thickness of unit
  - Net-to-gross – from lithological sections – eliminates non-reservoir intervals (mudstones, evaporites, tight carbonates)
  - Porosity – from reservoir or aquifer data
  - Storage efficiency – idealised range from closed system behaviour (0.5%) to open system aquifer (6%)
  - CO_2 density – constant 0.6 tonnes/m^3
- Ranges estimated and Monte Carlo Analysis of overall storage potential (Gtonnes)
- Negative correlation introduced (-0.75) between Play area and Storage efficiency to allow for small, localised reservoirs being potentially better exploited than large, dispersed areas
- Very wide uncertainty results

Rub’al-Khali Basin: Quantitative estimates of storage potential: Workflow

For each storage play

- **Range of storage play fairway area**
- **Range of reservoir thickness**
- **Range of reservoir net-to-gross**
- **Range of porosity**

Standard assumptions of

- **Range of storage efficiency up to 6%**
- **CO_2 density**

Standard assumptions of

- **Range of storage efficiency up to 6%**
- **CO_2 density**

Summation

- **Deterministic**
- **Probabilistic**

Rub'al-Khali Basin: Estimates of storage potential (Gtonnes CO_2)

Reservoir	Area	Low (P90)	Best (P50)	High (P10)
Umm er Radhuma	-	0.7	2.1	5.4
Wasia	Mishrif	3.1	8.2	20.0
	Burgan	3.2	8.9	21.6
Thamama	Hawar	5.3	13.2	31.0
	Zubair	0.7	1.9	4.8
Arab	North	0.9	2.4	6.1
	South	1.5	4.5	12.1
Araej	North	2.1	6.1	15.9
	South	0.3	0.7	1.7
Minjur	North	0.8	2.2	5.3
	Central	0.6	1.4	3.3
	South	0.4	1.0	2.4
Khuff	Khuff	0.5	1.3	3.2
	Unayzah/Haushi	2.6	7.6	21.2
Tawil	-	0.5	1.6	4.4
Tayma	North	4.0	13.5	37.9
	South	1.1	6.1	21.7
Saq	-	5.1	13.5	33.6
Total (Deterministic)		39.7	119.3	317.5
Total (Probabilistic)		108.5	150.1	209.2

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Oman Ophiolite: Estimate of storage potential

- Analogous pilot and experimental work has taken place in Iceland in the CarbFix project. Here CO_2 and H_2S are injected 750m below surface into hydrothermally altered basalts in an active volcanic area with an extremely high geothermal gradient. The ambient temperature in the injected zone is up to 250°C. Reactions are fast, with 90% of injected CO_2 estimated to be converted over year-decadal time scales.

- Precise P,T conditions and mineral suite may thus not be directly comparable to Oman, but volume estimates can be compared. Injection zones 100m thick over a field of 80km^2 are estimated to have a capacity of 2430 Mt CO_2 storage (Clark et al, 2020), but similar estimates range widely from 50-5000Mt.

- Based on the following assumptions:
  - Area of ophiolite 30 000km^2
  - 30% composed of prime harzburgite lithology
  - 30% of this directly associated with thick ophiolite slices and/or elevated geothermal gradient
  - Thickness of injected zone 100m
  - Storage efficiency 10% - this effectively relates to the proportion of the available porosity that is occluded by calcite and other carbonates. Previous estimates for Icelandic data range up to 100%.
  - This yields a tentative storage potential of **8.2 Gt CO_2 storage**

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Recent hydrogen developments in target countries (1/2)

Country	Developments
	• No announced projects yet – not clear whether Bahrain favours blue/green hydrogen but it lacks the oil/gas reserves that neighbours enjoy + installed renewable capacity is not sufficient to drive green hydrogen production • In November 2020, the investment and business development arm of the National Oil and Gas Authority (NOGA) signed an MoU with Air Products to explore the viability of deploying hydrogen as an avenue to reduce carbon emissions
	• Kuwait does not have any announced projects yet - not clear whether Kuwait favours blue/green hydrogen, the country has plenty of oil, and the installed renewable capacity is not sufficient to drive green hydrogen production • Discussions between the Kuwait Petroleum Corporation (KPC) and Kuwait Foundation for the Advancement of Sciences (KFAS) resulted in a white paper on potential opportunities of CCUS
	• Oman has announced five commercial-scale and pilot hydrogen projects – the country is leaning towards green hydrogen • The most notable project is led by a consortium of OQ, InterContinental Energy, and EnerTech which plan to build a 25GW multi-phased green fuels projects in Duqm • Other projects include ACME and Tatweer’s $2.5bn green ammonia plant, HYPORT Duqm 250-500MW green hydrogen project, and Sohar Port Pilot project

Recent hydrogen developments in target countries (2/2)

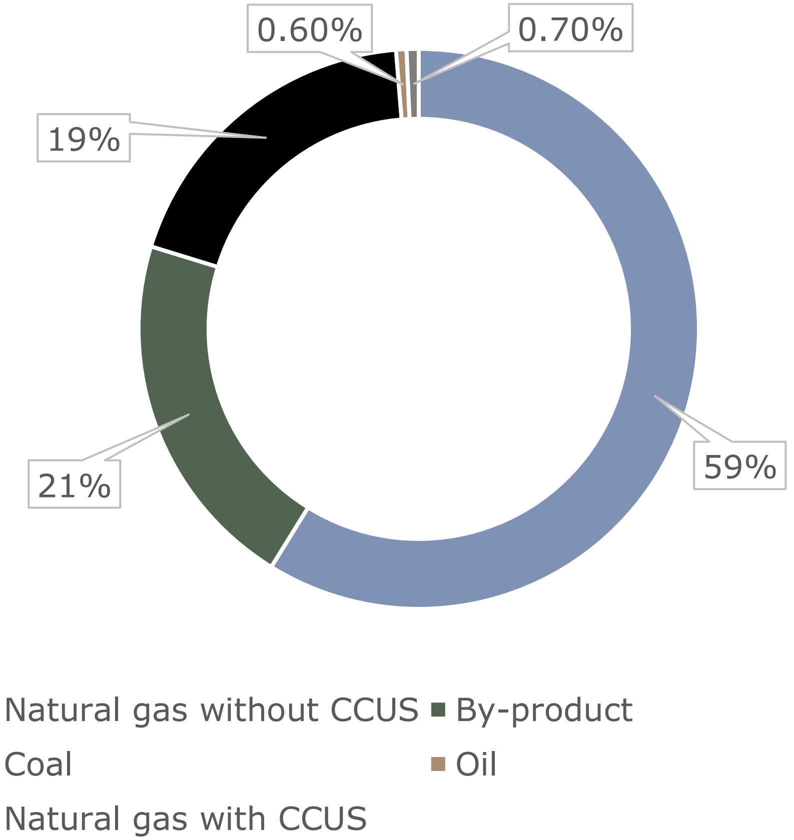
Country	Developments
	• No announced projects in Qatar. The country is already the leading grey hydrogen producer in the GCC region. Direction towards blue/green is not clear + insufficient renewables to drive green hydrogen production • In June 2021, Qatar National Research Foundation (QNRF) announced plans to launch a fund dedicated to exploring the prospects and opportunities of hydrogen energy in Qatar
	• Saudi Arabia has a blend of announced projects between grey/blue/green hydrogen – developing their renewable energy program – Vision 2030 • The $5bn agreement between Air Products, ACWA Power and NEOM to develop the world’s largest green hydrogen to ammonia plant • In January 2020, operations began on a $400 million hydrogen production site and a 15km pipeline in Yanbu • Air Products and Qudra Energy began constructing a 150,000 tonne/year SMR plant to produce hydrogen at Jubail Industrial City • Saudi Arabia sent the world’s first ever blue ammonia cargo to Japan to be used to produce emissions-free electricity
	• United Arab Emirates has a blend of announced projects between blue/green hydrogen – developing their renewable energy program – 2050 Strategy • DEWA commissioned that first pilot electrolysis plant in the GCC region in partnership with Siemens in May-2021 • Masdar and Siemens announced an electrolysis facility to produce fuels for vehicles in Masdar • ADNOC announced a 1 million tonnes per annum blue ammonia plant in Ruwais to feed its downstream petrochemical facilities • Helios Industry announced a 200,000 tonnes per annum project Khalifa Industrial Zone Abu Dhabi

In 2020, the majority of hydrogen was produced by SMR and coal gasification

COMMENTARY

- Steam methane reforming accounted for 59% of produced hydrogen in 2020 due to the maturity of the process, availability of natural gas, and its well-established infrastructure
- 79% of hydrogen came from dedicated hydrogen production plants and the remaining 21% were delivered by facilities designed for other products (for example, the reformation of naphtha into gasoline produces hydrogen in oil refineries)
- The share of coal in hydrogen production is already shrinking and oil contributes to less than 1% of hydrogen produced by dedicated units. This raises an important point on the capacity of blue and green hydrogen to replace coal and oil

GLOBAL HYDROGEN PRODUCTION IN 2020 (MTONNES)



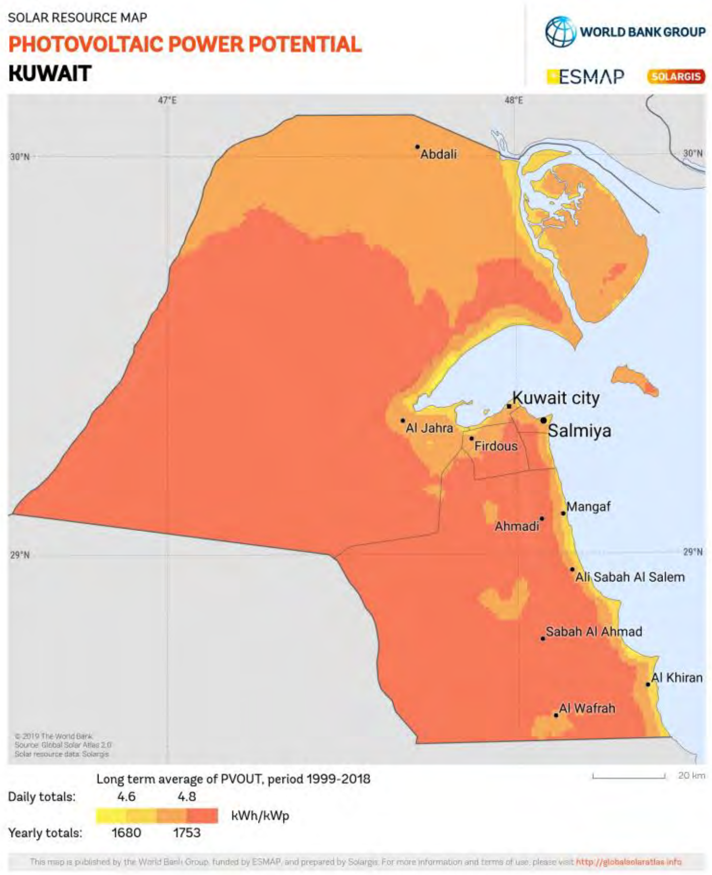
Source: IEA

Hydrogen in Kuwait is best suited to green for domestic demand but with some novel opportunities to pursue

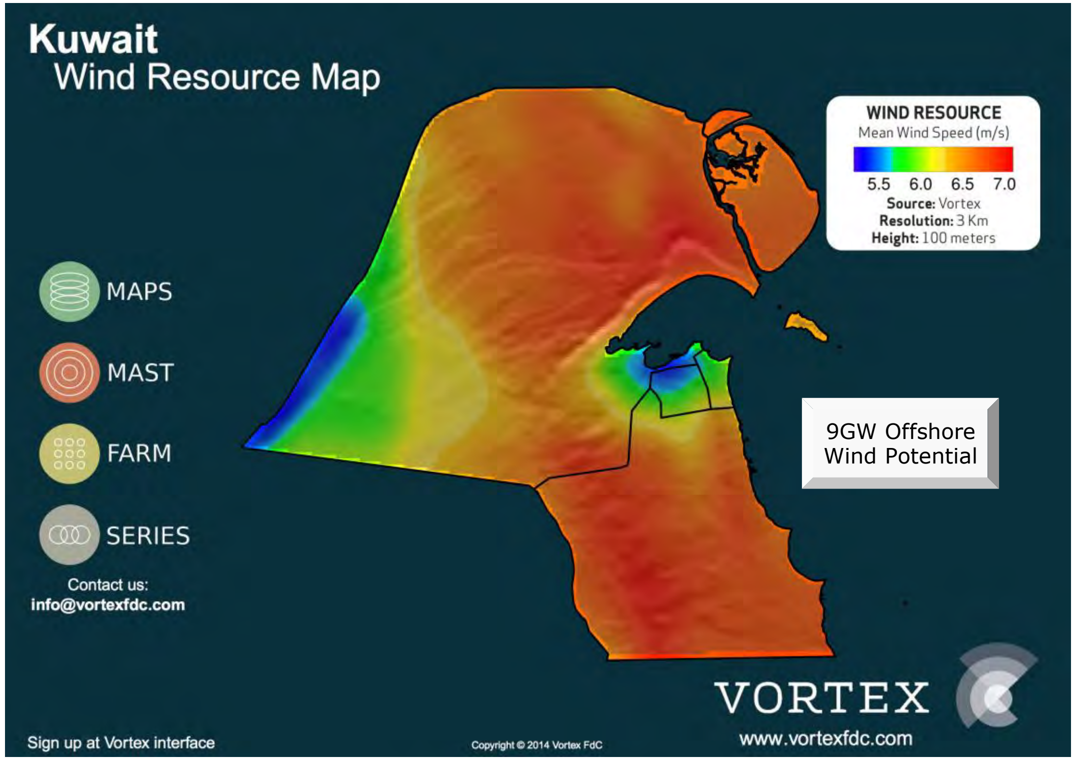
- Based on the data and analysis the Kuwait National Hydrogen Strategy (KNHS) needs to consider:
- As a net gas importer the scope for blue hydrogen in Kuwait is limited compared to its GCC neighbours
- Coupling blue hydrogen production with EOR for the short term makes most economic sense
- Turquoise hydrogen with an associated local market for carbon black is an option
- Green hydrogen would benefit from solar resources but scale is likely to be limited to domestic demand
- Oil based blue hydrogen looks to be expensive in the short term and unlikely to compete with other blue hydrogen and green hydrogen over the mid-long term
- There is an emerging commercial process from fire flood and POX that could make ‘red’ hydrogen without the need to produce the oil to surface that might make sense for the mid-long term in the case of stranded oil deposits
- CCS in the Wasia and Thamamma formations offers significant potential in the country which could support a blue hydrogen production base if enough cheap gas could be reliably procured
- 2050 emissions of 40-50Mt offer an opportunity for domestic consumption of hydrogen but this could be satisfied by green production
- Export potential would then be predicated on cheaper gas than the GCC neighbours or greater demand than they can fill

Green hydrogen from solar is a low hanging fruit with additional options from wind

SOLAR RESOURCE POTENTIAL



WIND RESOURCE POTENTIAL



Hydrogen strategy in UAE can deploy via multiple routes with a mix of green, blue and pink

- 2021 hydrogen roadmap targets 25% of global market share of low-carbon hydrogen by 2030 which is set at 500kt per year
- Unlocking new sources of value creation (‘low carbon’ products (steel, ammonia, kerosene/syn-fuels)
- Based on the data and analysis the U.A.E hydrogen strategy needs to consider:
- Desire to be self sufficient in gas will require extra investment if blue hydrogen is the goal
- As a net gas importer the cost is likely to be higher than GCC neighbours pursuing the same goal
- Desire for supporting new low carbon industries may favour turquoise hydrogen with end users of carbon black, depending on scale this may justify gas imports
- Green hydrogen would benefit from solar resources and plentiful land which could support an export market
- Pink hydrogen offers a further route to meet the export aspirations
- Carbon storage is largely found in the south of the country in the Rub’al Khali with multiple stacked formations suitable
- In addition there is extensive salt dome potential which would favour large scale storage of hydrogen and support a large production base
- Internal emissions of 118-122Mt suggest a sizeable internal market for hydrogen and coupled with the extensive port and export infrastructure a large scale hydrogen production base for export is likely feasible
- ADNOC already produces 300kt/year of hydrogen and plans to up this by 200kt/year

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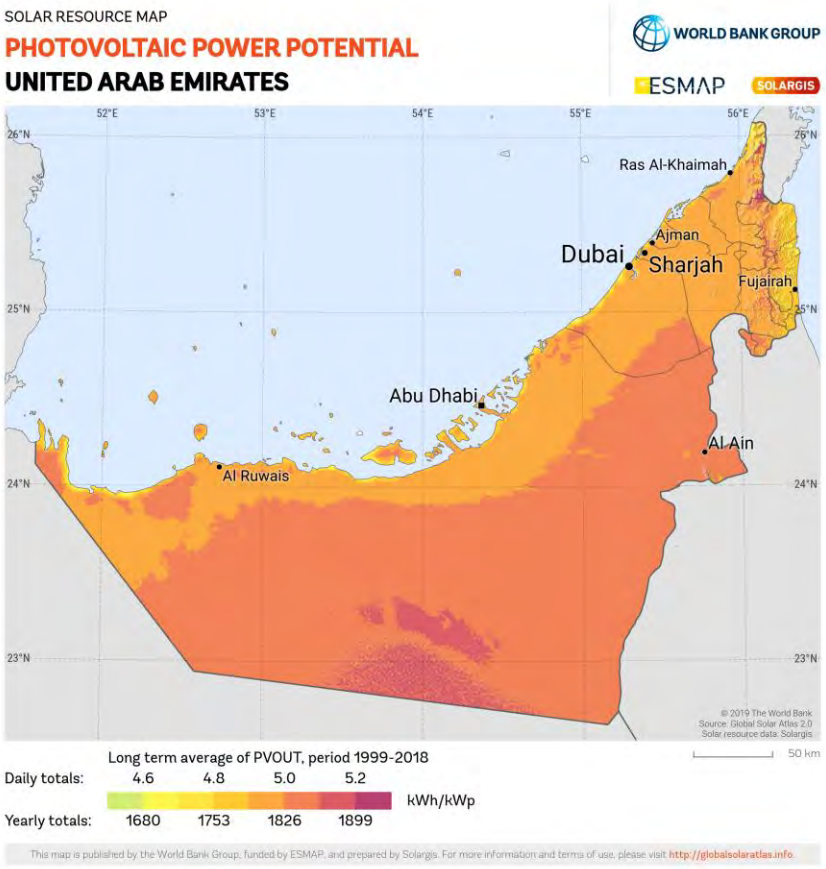
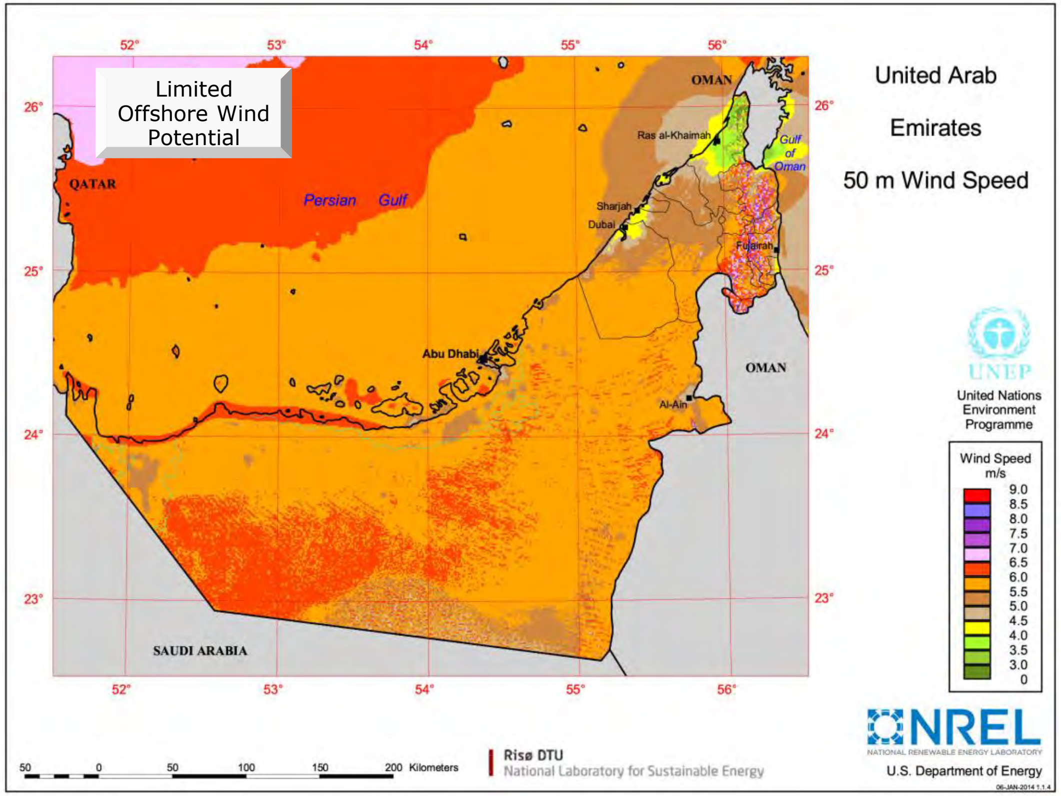
Good solar potential would support green hydrogen production in tandem with blue and pink hydrogen

SOLAR RESOURCE POTENTIAL



WIND RESOURCE POTENTIAL

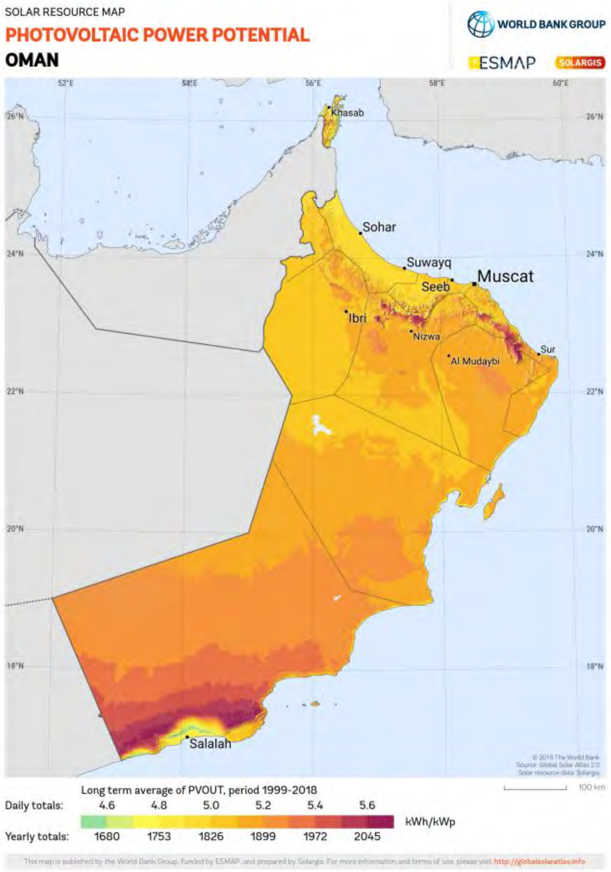


Oman has the potential for blue and green hydrogen but there is competitive advantage in going strong on green hydrogen

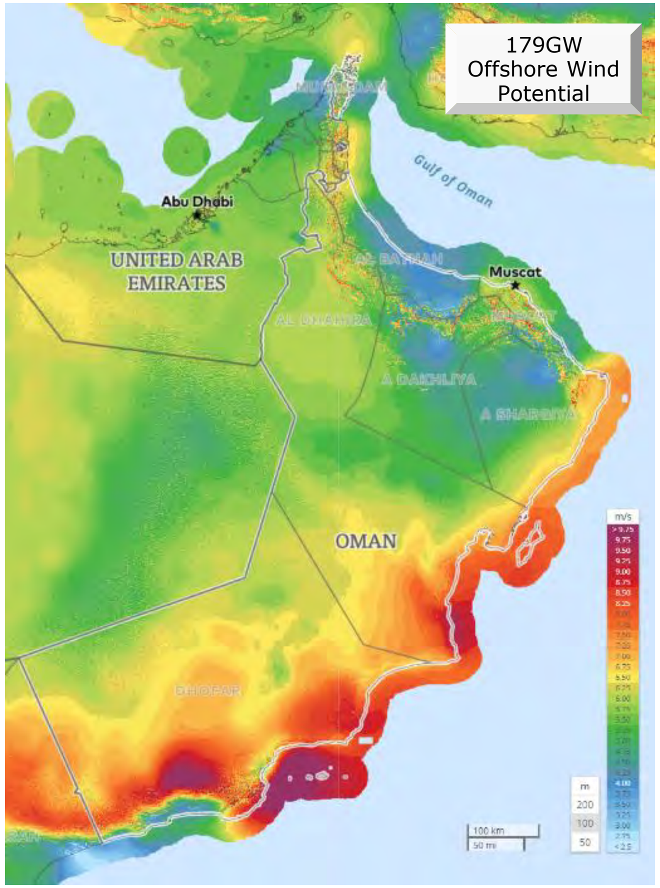
- Based on the data and analysis the Oman hydrogen strategy needs to consider:
- As a net gas producer, Oman is well placed to take advantage of blue hydrogen, but with domestic demand rising- and competition from Qatar it is not likely to be the cheapest supply
- Coupling blue hydrogen production with EOR to displace gas would be a low regret opportunity
- As with other GCC countries Turquoise hydrogen is an option but Oman’s best opportunity is green hydrogen
- The south of Oman has the potential to be a green hydrogen powerhouse with options for wind and solar that coupled with the Hyport project at Duqm offers great export potential to both Europe and Asia
- Not likely to be a large domestic market for hydrogen, but Oman could supply other members of the GCC with green hydrogen as well as generate exports to international markets
- Through the GCC electricity interconnection system Oman could also supply a ‘greener mix’ of grid electricity to power electrolysers throughout the GCC
- The Oman Ophiolite is expected to have the capacity for 8.2Gt of carbon storage and there is also opportunity in the Shuaiba and Arab formations which would also support becoming a carbon storage hub
- Emissions of 40-55Mt by 2050 suggest a smaller domestic market for hydrogen than the potential production which would favour exports

Southern Oman has plentiful solar and wind resources that make a green hydrogen hub viable

SOLAR RESOURCE POTENTIAL



WIND RESOURCE POTENTIAL

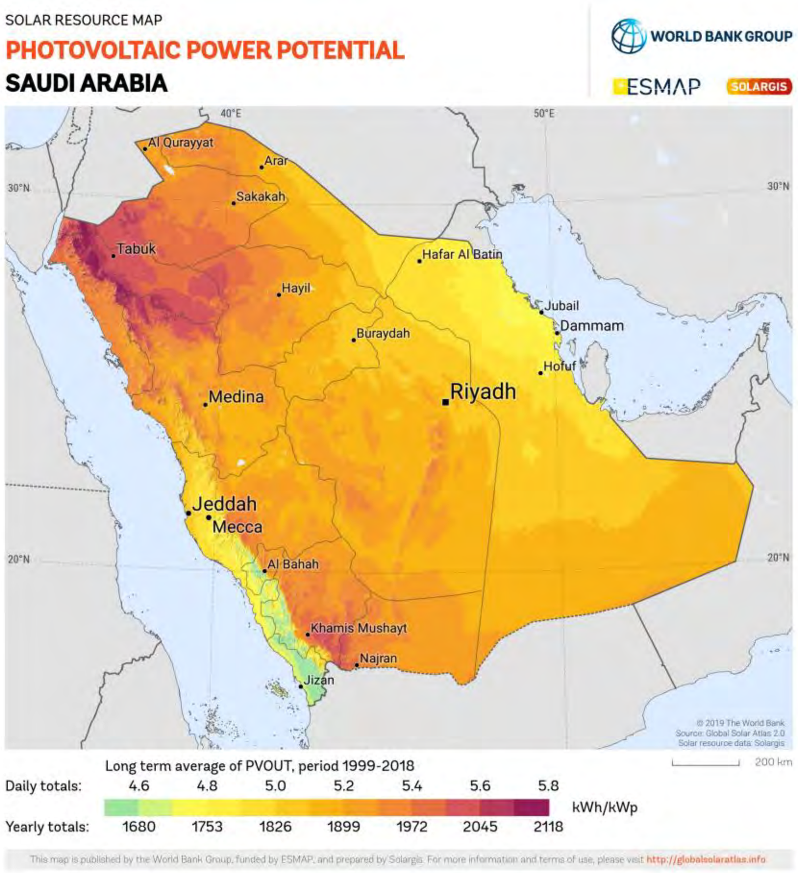


Hydrogen strategy in Saudi Arabia should follow a twin track approach which would allow exports at scale early and position for the move to green

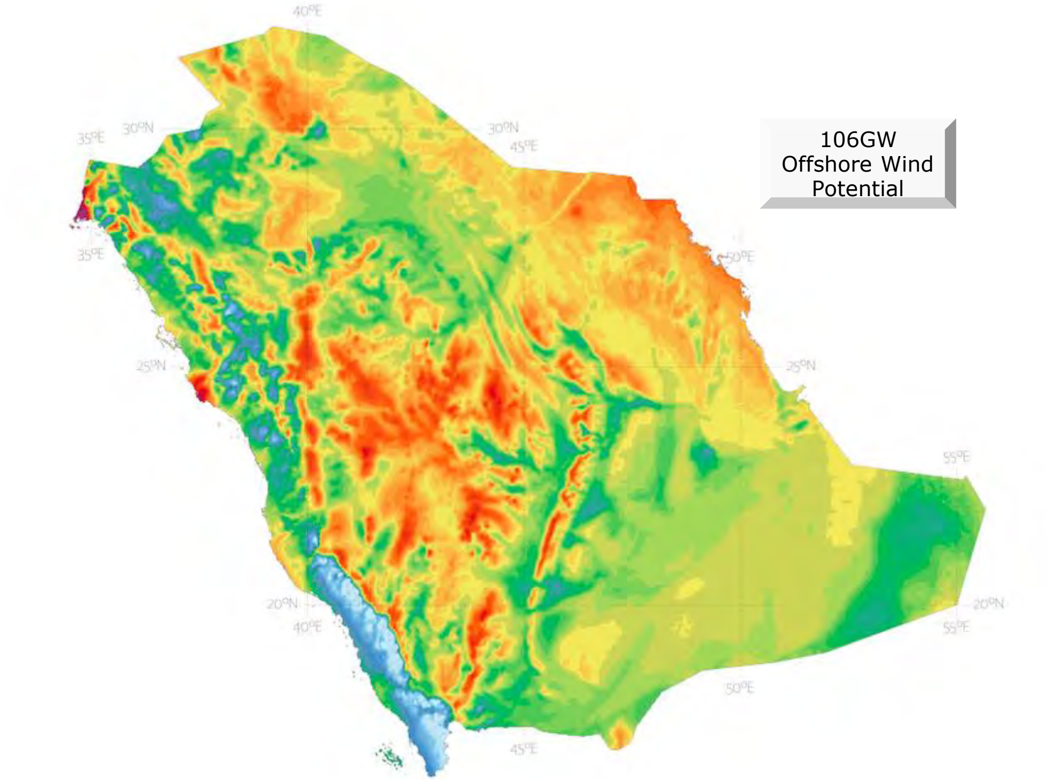
- Based on the data and analysis the Saudi Arabia hydrogen strategy needs to consider:
- As the source of the worlds cheapest barrels Saudi Arabia should expect to be the last oil producer standing and as such will need to use the associated gas
- Standalone gas fields and unconventional gas also provide an opportunity to build a sizeable blue hydrogen presence that would satisfy domestic and regional demand and provide additional volumes for export
- A blue hydrogen hub on the Gulf Coast to take advantage of existing infrastructure and demand makes sense
- The kingdom should not ignore its bounty of renewable energy across much of the kingdom and particularly in the NW but there is also opportunity for offshore wind too
- Hydrogen strategy should be coupled with a big push in renewables to decarbonize the electricity sector
- Also the potential to build new industry from carbon black based on the hydrogen from pyrolysis technique
- Saudi Arabia has committed to exporting 4Mt of hydrogen per annum by 2030 which will require large scale blue hydrogen plants
- Given the size and geology of the kingdom, Saudi Arabia is also well placed to be a hub for CCUS from its neighbours
- The Rub'al Khali has multiple stacked formations that would be suitable for CCS and suggest the potential for a regional hub for carbon storage (expected 120GT potential (Low 25Gt, High 470Gt)) as well as a large scale hydrogen producer
- Emissions for 2050 at 300-350Mt suggests a very large internal market for hydrogen is possible

Green hydrogen favours the NW whilst blue hydrogen favours the East, suggesting a twin track approach

SOLAR RENEWABLES POTENTIAL



WIND RENEWABLES POTENTIAL



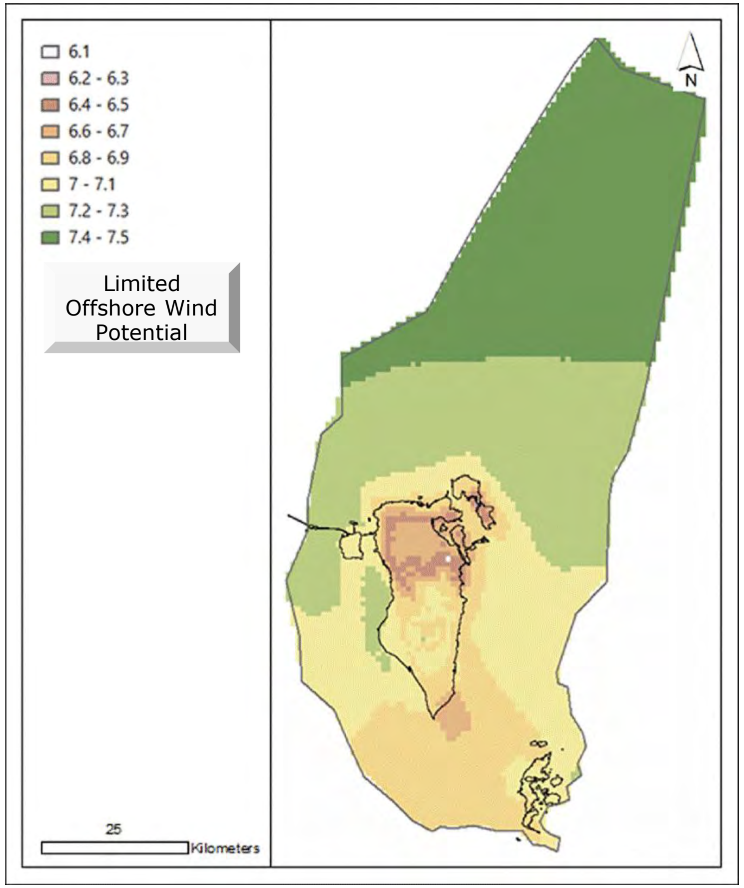
Hydrogen in Bahrain is best suited to green for domestic demand and imports from its neighbours

- Based on the data and analysis the Bahrain hydrogen strategy needs to consider:
- As a small gas producer and net gas importer there is no credible economic scope for blue hydrogen in Bahrain
- Green hydrogen would benefit from solar resources but scale is likely to be limited to domestic demand
- There is limited opportunity for carbon storage in Bahrain with only the Minjur Formation offering a viable target (but its properties are expected to be poor)
- This largely precludes blue hydrogen unless carbon is stored in Saudi Arabia (Kuwait and Qatar are also options but the larger distance challenges the economics)
- Internal emissions of 27-37Mt are expected by 2050 which means that domestic demand could likely be satisfied by green hydrogen and imports

Small scale green hydrogen from solar is possible but not likely to reach the scale needed for export

SOLAR RENEWABLES POTENTIAL

WIND RENEWABLES POTENTIAL

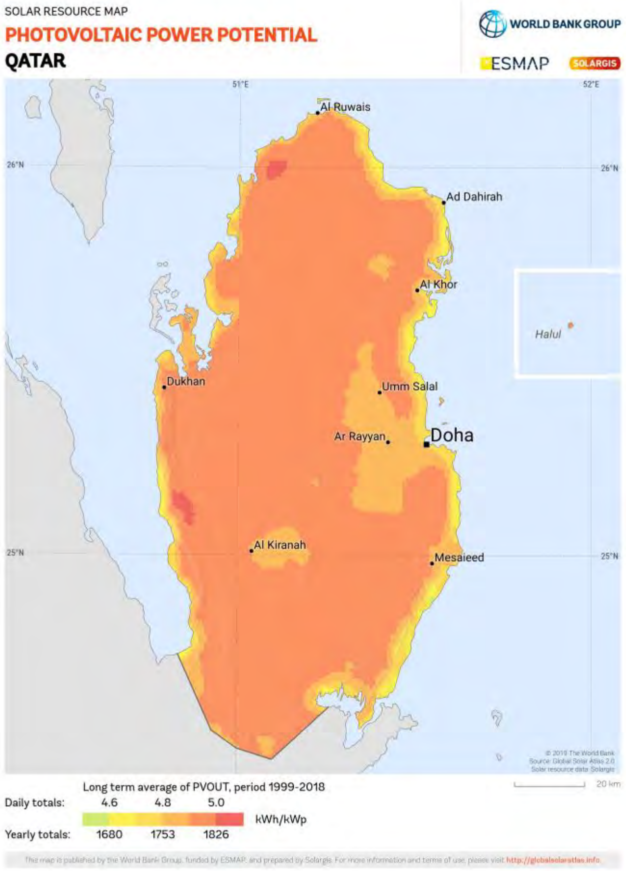


Hydrogen strategy in Qatar likely to be dominated by blue hydrogen, but with room for a sizeable solar green hydrogen component

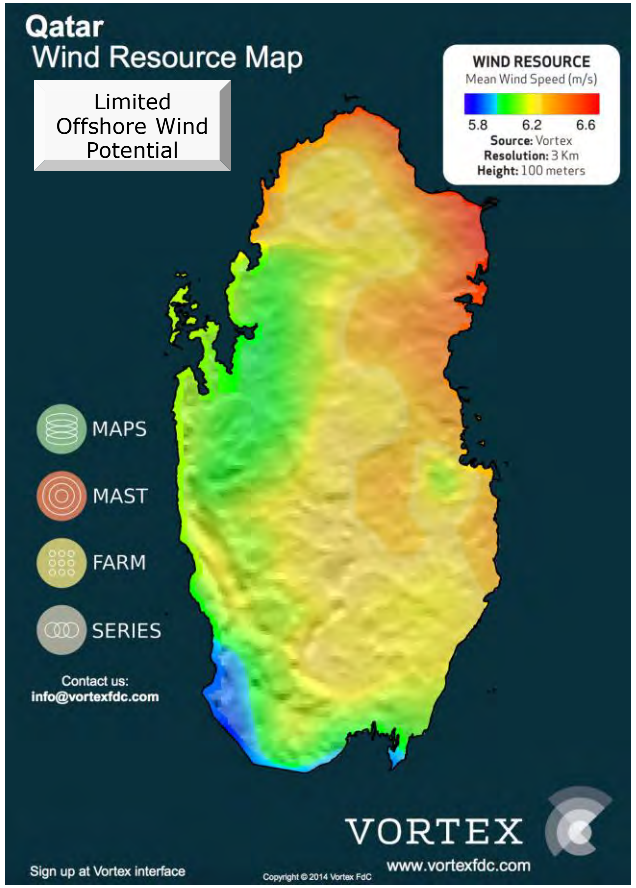
- Based on the data and analysis the Qatar hydrogen strategy needs to consider:
- With gas reserves in the TCF range Qatar has a massive endowment of the cheapest gas feedstock and should be looking to using this in blue hydrogen and turquoise hydrogen production
- With existing export infrastructure and expertise handling gases it would make sense to become a global supply hub for low carbon hydrogen
- Though possible to produce from solar, Qatar's small size will limit the scale of green hydrogen compared to its neighbours
- Its goal should be to supply the hydrogen to decarbonize the GCC and export the rest to Asia
- CCUS storage capacity in the offshore area is plentiful with potential targets in the Wasia, Shuaiba and Arab formations (Araej also present but expected to be poor)
- Internal emissions of 100-150Mt are expected by 2050, which gives a large potential domestic market as well as the opportunity to export hydrogen both regionally and globally

Green hydrogen from solar is possible but renewable endowment is lower compared to other GCC countries

SOLAR RENEWABLES POTENTIAL



WIND RENEWABLE POTENTIAL



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The GCC market has witnessed promising hydrogen initiatives over the past two years to support the development of a domestic hydrogen market

Country	Developments
	• In Nov-2020, the investment and business development arm of the National Oil and Gas Authority (NOGA) signed an MoU with Air Products to explore the viability of deploying hydrogen as a sustainable fuel in the transport sector as well as an avenue to reduce carbon emissions
	• Discussions between the Kuwait Petroleum Corporation (KPC) and Kuwait Foundation for the Advancement of Sciences (KFAS) resulted in a white paper on potential opportunities of blue hydrogen and the deployment of CCUS
	• Petroleum Development Oman (PDO) has hired Belgian company Hinicio to study their pilot green hydrogen project which will be used to asses to feasibility and potential scale-up of green hydrogen

The GCC market has witnessed promising hydrogen initiatives over the past two years to support the development of a domestic hydrogen market

Country	Developments
	• In Jun-2021, Qatar National Research Foundation (QNRF) announced plants to launch a fund dedicated to exploring the prospects and opportunities of hydrogen energy in Qatar
	• The most notable partnership is for the NEOM hydrogen plant which is jointly owned by Air Products, ACWA Power, and NEOM • In Apr-2021, Hyzon Motors and Modern Industrial Investment Holding Group formed a partnership to build a hydrogen-fuelled vehicle assembly factory in Saudi Arabia
	• DEWA has commissioned the first demonstrator plant in Dubai in May-2021 to showcase hydrogen-fuelled vehicles at Expo2020 • Masdar and Siemens plan to commission a demonstrator green hydrogen plant to support hydrogen mobility efforts in the city of Masdar in Abu Dhabi • In early 2021, ADNOC, Mubadala and ADQ formed a hydrogen alliance to attract more investment in hydrogen initiatives and support the burgeoning market • Al-Futtaim, Air Liquids and Khalifa University published a joint study on hydrogen mobility in the UAE

The GCC region plans to become a pivotal player in the global hydrogen export market and is well placed to do so

Country	Developments
	• We expect Bahrain to be a net importer of hydrogen for two key reasons: 1- Bahrain does not export or import any natural gas and the entire gas production is consumed locally leaving insignificant amounts for blue hydrogen production 2- The availability of land could pose a major problem for blue hydrogen as is the case of wind and solar technologies
	• We expect Kuwait to be a net importer of hydrogen as the country is a net importer of natural gas giving its neighbours a production cost advantage
	• HYPORT Duqm project will be developed in the Special Economic Zone at Duqm. The full value chain will be integrated and a brand-new export terminal at the Port of Duqm to respond to global demand for low-carbon hydrogen at its derivates. The first phase is planned to come into operation in 2026 • OQ, the state-owned oil and gas company, and Hong Kong based InterContinental Energy and Kuwait-based Enertech are planning a 10 Mtpa green ammonia project powered by 25GW of renewables. The plant is expected to reach full capacity in 2038 and most of the produced ammonia will be exported to Europe and Asia • ACME-Tatweer signed an MoU for a 2200 tonnes per day green ammonia project at the Special Economic Zone at Duqm. The plant is strategically planned to cater to international markets across Europe, Asia, and America

The GCC region plans to become a pivotal player in the global hydrogen export market and is well placed to do so

Country	Developments
	• Despite not announcing any pipeline projects or partnerships, Qatar is expected to be an active player in the hydrogen export market due to the availability of cheap natural gas resources coupled with large-scale LNG export capabilities
	• In Sep-2020, Saudi Arabia exported 40 tonnes of blue ammonia to Japan to launch clean ammonia cooperation efforts between the two countries. Japan utilised the imported ammonia for power generation • Helios Hydrogen plant in NEOM (4GW) is planned to become the first commercial green hydrogen plant in the GCC region with an expected COD in 2025. Air Products is the sole off-taker of the green ammonia which will be transported globally to power hydrogen mobility • The Saudi Ministry of Energy and German Ministry of Economic Affairs signed an MoU that establishes a common hydrogen vision to cooperate closely on the production, processing, use and transport of low-carbon hydrogen by sharing expertise and technological know-how. It also underlines Saudi Arabia's vision of becoming a global hydrogen exporter • ENEOS (Japan's largest refiner) started 2021 by signing an MoU with Saudi Aramco to consider the development of CO_2 free hydrogen and ammonia supply chains
	• Helios Industry, a special project vehicle, announced the first commercial-scale (800MW) green ammonia project in the UAE with an expected COD in 2024 • ADNOC announced the first blue-ammonia project in Ta'ziz industrial complex in Ruwais with an expected capacity of 1 Mtpa • Mubadala signed an MoU with Italian infrastructure company Snam in Mar-2021 to develop hydrogen projects in the UAE and internationally • The UAE government expressed interest in pursuing green hydrogen through the Emirati-German Energy Partnership which was launched between the UAE Ministry of Energy and Industry (MOEI) and the German Ministry of Economic Affairs and Energy (BMWi) • ADNOC has concluded partnerships with Petronas of Malaysia, South Korea's GS, Japan, and few German firms • The Department of Energy in Abu Dhabi signed an MoU with Marubeni to establish a hydrogen-based society

A summary of the key assumptions used in the LCOH calculation

Category	Assumptions
Reforming technologies without CCUS	The reported capex for a 300MW SMR facility is between $166-282 million while for the same ATR capacity it is between $277-820 million. Fixed opex values are assumed to be 4% of the capex for both technologies based on the convention followed in the IEA's Future of Hydrogen report assumptions
Reforming technologies with CCUS	BEIS Hydrogen Production Costs 2021 report is used as the main source for the capex of reforming technologies with CCUS. A project size of 300MW was used a reference for the calculation
Variable costs	The variable cost of operating an SMR facility is driven by natural gas consumption whereas ATR units consume electricity in additional to gas to power the air separation unit. The split between electricity and gas related variable costs is 82% to 18% according to BEIS Hydrogen Production Costs 2021 report
Gas prices	AFRY's view on natural gas prices in each GCC market (net importer, net exporter, self-sufficient)
Hurdle rates	We assume that the hurdle rate in each market decreases by 1.5% during the modelled period as more CCUS capacity is deployed
Learning curves	The learning curves of SMR and ATR without CCUS are not steep as technologies are already mature and well-established. On the other hand, a steeper learning curve is applied to SMR and ATR with CCUS driven mostly by CCUS cost reductions
Carbon prices	We exclude any carbon prices or taxation from the analysis

Sources: AFRY, BEIS,

Gaffney Cline AFRY ÅF PÖYRY